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Life Cycle Inventory of Australian Forestry and Wood Products

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Life Cycle Inventory of
Australian Forestry and Wood Products

Prepared for

Forest & Wood Products Australia

By

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ALCAS	Australian Life Cycle Assessment Society
AusLCI	Australian National Life Cycle Inventory Database
CORRIM	Consortium for Research on Renewable Industrial Materials
FWPA	Forest and Wood Products Australia
Glulam	Glued Laminated timber
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LVL	Laminated Veneer Lumber
MDF	Medium Density Fibreboard
OSB	Oriented Strand Board
T&G	Tongue and Groove

EXECUTIVE SUMMARY

Introduction

Over recent years there has been a growing recognition that consumption of manufactured products affects both resources and the environment and that the production of a product impacts the environment, beginning with the extraction of raw materials, through processing, subsequent manufacturing, use and disposal, as well as all necessary transportation.

There is limited verified life cycle information available on forestry and wood products and Life Cycle Inventory (LCI) information for wood products is currently the least well defined of any Australian LCI database. Organisations such as CORRIM in North America have worked with a variety of stakeholders over several years to produce an extensive publicly available LCI of forestry and wood products in the United States. Of the available LCI data for wood products used in Australia, few are based upon detailed analysis of the Australian forestry and wood products industry.

A thorough and detailed approach was undertaken to develop a LCI database of representative forestry operation and wood products and processes used in Australia. The LCI database is compatible with international standards and with an Australian National Life Cycle Inventory Database (AusLCI) the specifications of which are currently being determined.

Life Cycle Assessment

Life Cycle Assessment (LCA) is an objective process to evaluate the environmental burdens associated with a product or process over its life cycle by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements. “Life cycle” refers to all activities from acquisition of raw materials through product manufacturing to the end use of a product and its eventual disposal or recycling, i.e. from “cradle-to-grave”.

The key component is the inventory (known as a Life Cycle Inventory) which contains the values of all the inputs and outputs for relevant activities undertaken to produce a product. The scope of a typical LCI includes the inputs and outputs up to the factory gate, i.e. up to when a product is produced for a market as the subsequent inputs and outputs depend on the specific application of that product.

Australian LCI of forestry and wood products

The overall objective was to create the first national, rigorous LCI of representative Australian forestry and wood products to enable evaluation and benchmarking of the environmental impacts of wood products for comparison with competing products and for life cycle assessment.

The LCI database for forestry and wood products aimed to be of high quality, contain a range of representative products, and be consistent, credible, and demonstrably independent. Practicalities such as focusing on a limited but representative range of wood products, availability of resources, and availability of data meant that many decisions were made on what would constitute a satisfactory LCI database.

The data collection was up to the consumption phase for the wood products when sold to a consumer (known as a cradle-to-gate study). The cooperation of industry was excellent and resulted in good quality data and desired industry coverage. This provided an accurate database of Australian wood products for various users to examine a wood product and consider its production history.

The Australian LCI database of forestry and wood products covers the following categories: softwood plantation and native hardwood forests; softwood framing and hardwood timbers; veneer, plywood, and laminated veneer lumber (LVL); particleboard and medium density fibreboard (MDF); and glulam and engineered I-beams. While the original aim was to develop LCIs for generic wood products, the detailed data was sufficient to provide information on common categories of the generic products. Table 1 shows the categories of products and the expanded (more specific) range of products developed for the Australian LCI database and the coverage of Australian production.

Table 1 Products in the LCI database

Category	Products	Coverage of Australian production (approx %)
Logs – Softwood	Peeler log, High quality saw log, Low quality saw log, Chips	50
Logs – Hardwood	Peeler log, Saw log	22
Sawn timber – Softwood	Rough sawn green timber, Rough sawn kiln dried timber, Planed kiln dried timber	40
Sawn timber – Hardwood	Rough sawn green timber, Rough sawn kiln dried timber, Planed kiln dried timber	30
Plywood	Interior Plywood, Exterior Plywood, Formply, Tongue and Groove Flooring, Structural Plywood (each 3 thicknesses)	90
Laminated veneer lumber (LVL)	LVL (3 thicknesses)	60
Particleboard	Raw and Decorated (each 3 thicknesses)	64
Medium density fibreboard (MDF)	Raw and Decorated (each 3 thicknesses)	92
Glued laminated timber (Glulam)	Pine	55
I-beams	Oriented strand board (OSB) web and pine flanges, Plywood web and LVL flanges	65

Guidelines, documentation and quality assurance

There are established guidelines for creating a LCI database in the form of the ISO 14040 series of standards, including ISO 14044 Life cycle assessment — Requirements and guidelines and ISO/TS14048 Life cycle assessment — Data documentation format.

A quality assurance plan was put in place and data documentation spreadsheets developed with accompanying checklists to ensure documentation met ISO standards for specifying the product system to be studied; functions of the product system; functional unit; system boundary; allocation procedures; data requirements; assumptions; limitations; data quality requirements; type of critical review, if any; and type and format of the report required for the study. An example of the detailed specifications is the system boundaries as shown in Figure 1 for sawmill products.

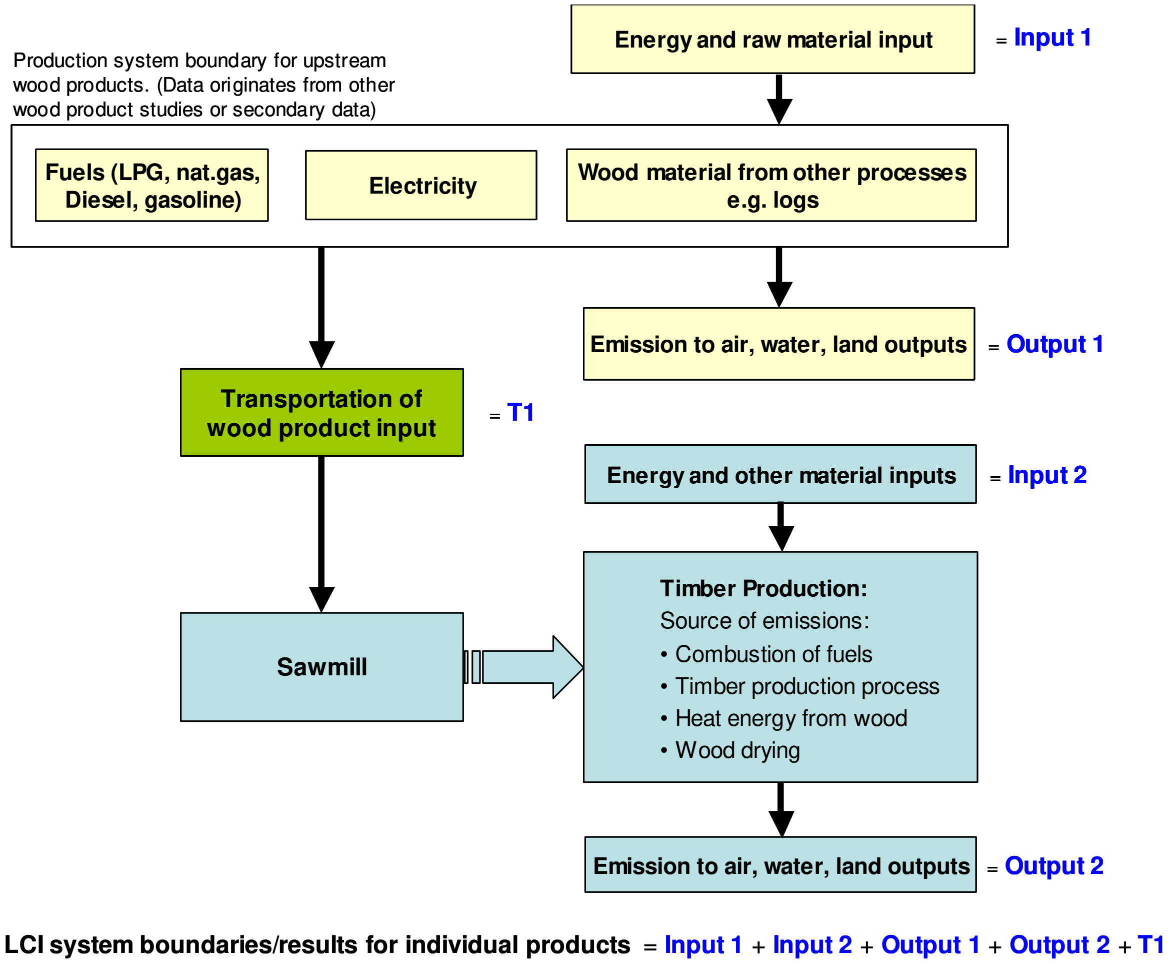


Figure 1 System boundaries for sawmill products

The raw materials in Figure 1 are the materials obtained directly from the environment. The inputs in Figure 1 may contain common or pre-defined processes which can be called upon by any of the inventory product models. The common processes include logs from forests, adhesives, imported products and materials (adhesives and wood products such as oriented strand board (OSB)), energy supplies (electricity, gas, etc), transport modes (ships, aircraft, rail, trucks, cars etc.) and processing equipment. The output products include the main product, by-products and wastes.

Data collection

Survey forms identifying all required data were developed in collaboration with relevant industry input from each of the five areas: forestry, sawmills, veneer and plywood, particleboard and MDF, glulam and engineered I-beams. From a comprehensive list of Australian forests, sawmills and wood product manufacturing plants, a list of the industry providers of forestry and wood products that would be sufficient to achieve a target of 50% of Australian production was drawn up and approached for participation in the surveys. Typical forests, mills and plants were visited for visual inspection, initial data collection and identification and understanding of processes.

Seven case study regions – softwood plantations in the three States of Australia; and native hardwood regrowth forests also in three States of Australia - were the representative sources of forestry data.

Because of the large number and varying scale of sawmill operations and the changing structure of the hardwood industry; in particular, a sampling procedure was set up to capture data from as many as possible of the larger sawmills (approximately 22 softwood mills and 66 hardwood mills) using detailed data surveys. A simplified data form was sent to the mills to increase the response rate and supported with a number of site visits.

For the remaining plants manufacturing wood products in Australia, in any one category, there are less than ten producing almost all of the production in Australia so plants producing up to 80% of Australian production were approached. Where clear differences in processes among the plants could be identified, effort was made to include representatives of each identified type. The resulting coverage is shown in Table 1 for each category of forestry and wood product. Cooperation levels were generally very high and some very detailed data was made available thus ensuring a thorough understanding of the processes, their inputs and outputs and comprehensive maps of the processes.

Environmental impact modelling

From the visits to forests, mills and plants, comprehensive process maps were drawn up and then related individual processes were aggregated into a small number of processes which became the unit processes required of a LCI. The selection of unit processes was based on clearly defined steps in the process of producing the output products and influenced by the availability of data (or lack of being able to disaggregate available data). The data inputs and outputs per reference unit (e.g. usually m^3 or m^2 of a standard product) were then averaged for input into models developed in the SimaPro life cycle assessment software for all products. The integrated SimaPro model was then used to calculate the aggregated inputs and outputs per reference unit including all raw materials from forests and common processes such as Australian energy sources. The result was a LCI of all inputs and outputs for the products listed in Table 1.

Key results

Forestry

The forestry process includes the establishment, growing and management of forests, harvesting of trees and transportation of logs to processing facilities. It was assumed that the forests were in a steady state with no change in carbon stocks, management inputs or logs and chips outputs over time. Newly established plantations on ex-agricultural or native forest land and logging of old growth forest (for the large part) were excluded from this study.

Inputs considered in the forestry production systems included: land, water, fuel/energy, chemicals and other materials (other resources and consumables). Averaged over the production cycle, land use efficiencies ranged from 0.05-0.10 ha m^{-3} for softwood plantations and 0.11 - 0.98 ha m^{-3} for native hardwood forests. Estimated relative water-use (i.e. water use associated with forests less the water use associated with the applicable reference land use) ranged from 0.07 to 0.23 ML m^{-3} for softwood plantations compared with 0.15 to 1.25 ML m^{-3} for native hardwood forests. These native hardwood forest differences were largely a result of the lower management and harvesting intensity of native forests compared with softwood plantations.

Direct energy use varied from 183 MJ m^{-3} in softwood plantations to 356 MJ m^{-3} in native hardwood forests. Virtually all (>99%) energy use was associated with combustion of diesel in vehicles and machinery. The greater energy usage in native hardwood forests was largely due to greater fuel usage during harvesting (174 MJ m^{-3} compared with 73 MJ m^{-3} for softwood plantations) and haulage (148 MJ m^{-3} compared with 91 MJ m^{-3} for softwood plantations). For softwood plantations, the largest contributor to direct energy inputs was haulage (48%), followed by and chipping (40%), establishment (4%) and roading (3%). For hardwood native forests, the largest contributor to total fuel and energy inputs was harvesting (50%) followed by haulage (41%) and roading (7%).

Estimated CO_2-e sequestered by the forest and stored in wood products averaged 830 kg m^{-3} for softwood products and 1030 kg m^{-3} for hardwood products.

Direct emissions include both CO_2 and non-CO_2 emissions from operations under the control of the forest owner or contractor (e.g. fertiliser, burning or vehicle and machine use). Direct CO_2 emissions averaged 19 kg CO_2 m^{-3} for softwood plantations and 57 kg CO_2 m^{-3} for native hardwood forests. Fuel reduction and slash burning were important contributors to total direct greenhouse gas (GHG) emissions accounting for 56% (32 kg m^{-3}) of total direct GHG emissions in native hardwood forests and 24% (4 kg m^{-3} in softwood plantations). For burning, only non-CO_2 emissions (CH_4 and N_2O) were included as CO_2 emissions were assumed to be re-sequestered under the steady state approach. Total indirect emissions from upstream processes (production and supply of energy and materials) contributed 7 kg CO_2-e m^{-3} to softwood plantations and 9 kg CO_2-e m^{-3} to native hardwood forests. Thus, indirect emissions comprised 27% of total emissions (26 kg CO_2-e m^{-3}) for softwood plantations and 13% of total emissions from native hardwood forests (65 kg CO_2-e m^{-3}, Table 2).

Assumed CO_2 sequestered by the forest and stored in wood products averaged 830 kg m^{-3} for softwood products and 1030 kg m^{-3} for hardwood products (Table 2). Thus, total CO_2-e emissions from producing a log represent just 3% of the total CO_2-e sequestered in an average softwood log and 6% of the total CO_2-e sequestered in an average hardwood log (Table 2).

Table 2 CO_2-e emissions from production of logs from softwood plantations and native hardwood forests compared with sequestered CO_2-e

Product	**Total CO_2-e emissions (kg CO_2 m^{-3})**	**Total CO_2-e sequestered (kg CO_2 m^{-3})**	**Net CO_2-e emissions (kg CO_2 m^{-3})**
Softwood			
Average log	26	830	-804
Establishment and management (excluding burning)	6		
Burning	4	na	na
Harvesting	6	na	na
Haulage	9	na	na
Large saw log	41	810	-769
Medium saw log	32	820	-788
Small saw log	23	860	-837
Pulp log	11	830	-819
Chips (in field)	27	810	-783
Other log	22	820	-798
Hardwood			
Average log	65	1030	-965
Establishment and management (excluding burning)	4		
Burning	32	na	na
Harvesting	14	na	na
Haulage	15	na	na
Veneer log	190	1230	-1039
Saw log high quality	125	1050	-925
Saw log low quality	52	1130	-1078
Pulp log	48	1000	-953
Other log	348	1300	-952

Softwood framing and hardwood timbers

The main sawn wood products in the study in terms of economic value for softwood was structural framing and for hardwood it was floorboards and other dressed timbers. Softwood sawmills also gained some additional value from wood chips. However, for medium to large hardwood sawmills in the survey, the additional economic value from other sawn products such as pallet and residues was very small relative to the high value products with consequent small contributions in a LCI. The recovery rates of sawn timber product from logs (45% for softwood and 36% for hardwood mills) reflect the different species used, log size and quality, as well as the level of processing for the different mix of wood products.

Wood residues were the main source of thermal energy for wood drying for both hardwood and softwood mills and was also the main energy source. These wood residues are used as hogged fuel which is sawmill refuse that has been fed through a disintegrator, or hog, by which the various sizes and forms are reduced to a practically uniform size of coarse chips or shreds; bark, sawdust, planer shavings, wood chunks and fines are included. The burning of wood residues generates carbon dioxide which is balanced by the growing of the timber and carbon dioxide sequestration. Electrical energy is relatively small (< 100 kWh m^{-3}) in terms of energy used on-site but accounts for approximately 20-40% of primary energy use and greenhouse gas emissions.

Other air emissions are released from fuel combustion as well as from the timber as it dries. These emissions become important for potential health impacts assessed using LCI data (e.g. with Eco-indicator 99).

Water use was similar but smaller for hardwood sawmills (280 Lm^{-3}) compared to softwood mills (360 Lm^{-3}) for kiln drying. In contrast, softwood sawmills reported relatively small water usage for other purposes. Most mills reported the supply as mains water.

Water emissions include Biological Oxygen Demand (BOD) and suspended solids and are largely related to site runoff from the log yard (although difficult to quantify) and water emissions from the kiln are also important. Water emissions and solid wastes were based on detailed monitoring for only one large Australian softwood sawmill (e.g. 0.0057 kg m^{-3} of BOD).

Table 3 illustrates that the results are within or close to the range of published data from the international literature for a selection of key measures. The sources also allow differences in other measures between hardwood and softwood to be examined.

Table 3 Comparison of sawn hardwood and softwood data with international literature

Data type	Hardwood	Softwood	Literature
Recovery	36%	45%	28% - 58%
Water (tonnes/m^3 of sawn product)	0.70	0.40	0.14 -1.7
On-site electricity (GJ/m^3 of sawn product)	0.50	0.36	0.21-0.5
Carbon dioxide (tonnes/m^3 of sawn product) - on-site emissions - boiler and mobile plant	0.37	0.46	0.26-0.35 (based upon CORRIM only)

Veneer, plywood and LVL

Data for veneer, plywood and LVL was collected from 80% of Australian plywood and LVL mills making this the most comprehensive analysis of these products undertaken, providing a new Australian benchmark. The plywood and LVL processes were compared and considered similar which enabled the use of plywood data in the LVL model. The results were generated by the SimaPro software using the updated data libraries. The results are for average Australian veneer, plywood and LVL which includes both hardwood and softwood veneer. The veneer process has four unit processes within the system boundary (preparation, conditioning, green veneer, dry and finish). The plywood and LVL processes both have three unit processes (manufacture, finish, and packaging). There is also a separate boiler process and an adhesive-mixing unit process which have been detailed as separate unit processes using available secondary data.

The input, output and emissions tables for veneer, plywood and LVL contain accumulative cradle-to-gate values. The main inputs to manufacture 1m^3 of average Australian plywood are listed in Table 4 and include energy to produce veneer. It requires 2.1 m^3 of logs to produce the veneer to make 1m^3 average Australian ply. The average results show that the yield of veneer from logs is approximately 47% compared to 50% estimated by CORRIM but varied between mills, with small labour intensive mills reporting higher recovery rates.

The main consumer of energy per m^3 is the boiler (7.17 GJ) which is primarily used in the veneer drying process. The electricity input is 156 kWh m^{-3}; LPG is 3.37 L m^{-3}; and natural gas 0.47 GJ m^{-3}. These energy sources are mainly used in the drying process (40% in drying). In addition, 328 L m^{-3} of water is also consumed.

The pressing process in plywood manufacture accounts for about 70% of CO_2 release, and of this, only 10% is attributed to the actual pressing process with over 30% originating from oil and gas production, and 30% from diesel production.

Table 4 Inputs to produce 1 m^3 average Australian plywood including energy from veneer production

Material Inputs	**Quantity**	**Unit**
Veneer from veneer process	0.92	m^3
Purchased veneer		
Phenol Formaldehyde Adhesive	53.60	kg
Urea Formaldehyde Adhesive	0.06	kg
Flour	5.60	kg
Filler	3.97	kg
Phenolic Overlay sheets	10.70	kg
Acrylic Putty	0.58	kg
Phenol Formaldehyde Putty	0.20	kg
Paint	0.475	kg
Ink	0.013	kg
Preservatives	0.059	kg
Plastic	0.24	m^2
Strapping	0.15	kg
Total Energy including veneer production		
Electricity	155.80	kWh
Natural Gas	466.00	MJ
LPG	3.37	l
Hogged Fuel	7168.00	MJ
Mains Water	328.00	l

Particleboard and MDF

For particleboard, data was collected from five plants covering 78% of the Australian production capacity. The data from one plant, however, was of insufficient quality and so was not included in the study, reducing overall coverage to 64% of the Australian production capacity. As the metering in the plants was unable to break the manufacturing process down to individual unit processes, the plants were modelled as a single process. Similarly, MDF manufacture was modelled as a single process, with data collected and modelled from three plants representing almost 92% of the production. The outputs from both particleboard and MDF manufacture were then used to model individual products, with wax quantity, and adhesive type and quantity, dependent on the final product.

Lamination data was collected from two plants, although one was not included in the study as it was of insufficient quality. Previous data collected from the excluded plant was used to provide an average for the lamination process.

The main inputs to particleboard and MDF manufacturing in this study (FWPA LCI), and their comparison to Ecoinvent 2 (Ecoinvent, 2007), an international (mainly European based) LCI database available with SimaPro and an Australian study by Grant (2005) are shown in Table 5 and Table 6.

Table 5 Comparison of particleboard manufacture with Ecoinvent 2 and Grant data

Inputs	Units	FWPA LCI	Ecoinvent 2	Grant (2005)
Material Inputs				
Wood (BDT)	kg	721	666	776
Adhesive	kg	65	51	67
Wax	kg	9.9	11	7.5
Ancillary materials				
Water consumption	L	213	304	160
Energy Inputs				
Total energy input	GJ	2.96	1.80	3.57

Table 6 Comparison of MDF manufacture with Ecoinvent 2 and Grant

Inputs	Units	FWPA LCI	Ecoinvent 2	Grant (2005)
Material Inputs				
Wood (BDT)	kg	780	720	797
Adhesive	kg	73.8	50	47
Wax	kg	7.1	21	5.2
Ancillary materials				
Water consumption	l	822	180	1,168
Energy Inputs				
Total energy input	GJ	5.25	5.72	6.30

Glulam and engineered I-beams

Australian average glulam requires 501 MJ of energy to manufacture 1 m^3 of glulam compared to CORRIM's 893 and 1417 MJ/ m^3 for Pacific North West (PNW) and South East (SE) respectively. Manufacture of Australian glulam consumes a little more electricity, requiring 365 MJ compared to CORRIM's 304 MJ for PNW and 356 MJ for SE. Other energy sources are mainly natural gas for Australian glulam, while other energy for PNW is predominantly hogged fuel and natural gas and for SE almost entirely natural gas.

Table 7 Comparison of energy requirements for 1 m^3 of glulam manufacturing

	FWPA LCI*	CORRIM (PNW)**	CORRIM (SE)***
Electricity (MJ)	365	304	356
Natural gas (MJ)	96	153	1024
LP Gas (MJ)	29	41	0
Kerosene	0	0	0
Diesel (MJ, 36.7MJ/L)	11	13	24
Gasoline (MJ, 32MJ/L)	0	3	13
Hogged fuel (MJ)	0	379	0
Total energy consumption (MJ)	**501**	**893**	**1417**
Comparison ratio (%)	100%	178%	283%

*Australian glulam weight averaged
**CORRIM (Pacific North West Area)
***CORRIM (South East Area)

The manufacture of 1 m^3 of glulam in Australia requires 668 kg of sawn timber (very similar to CORRIM's 592 kg for PNW and 676 kg for SE) and 64.8 kg of shavings and trimmings and 63.4 kg of sawdust including wood waste are generated respectively. Wood recovery for glulam in terms of wood input as sawn timber and output as glulam was estimated at 81%, the rest being shavings and trimmings and sawdust, which is similar to CORRIM's data (82%

for PNW and SE). The manufacture of 1 linear metre of I-beam, OSB web and pine flanges requires 9.3 MJ and 8.9 MJ for plywood web and LVL flanges, respectively.

Table 8 Glulam product yields comparison

Wood Mass Balance (weighted average)	FWPA LCI*	CORRIM (PNW)**	CORRIM (SE)***
Input (kg/m^3)	668	592	676
Output - Glulam (kg/m^3)	540	483	551
Output – shaving, trimming & sawdust (kg/m^3)	128+	109	125
Output - wood waste (kg/m^3)			
Recovery of wood (%)	81	82	82

+Wood waste involved in shaving, trimming and sawdust
*Australian glulam weight averaged
**CORRIM (Pacific North West Area)
***CORRIM (South East Area)

Benefits

The development of a LCI for Australian forestry and wood products is a major step in the provision of quality data on the environmental impacts of wood products. The wide forestry and wood industry coverage also makes the LCI database very representative of Australian wood products and an excellent basis for assessing the environmental impacts of any application of wood products.

Collection, enhancement and verification of data provide the industry with reliable environmental impact information to improve environmental performance as well as providing data for future assessment of choice in building products on the basis of environmental impacts. This potentially means greater acceptance of wood as an environmental material choice, give wood products a greater prominence in evaluation tools, and greater understanding by the industry of future growth areas, such as recycling opportunities and take back schemes.

The first national LCI database on Australian forestry and wood products production delivers:

- An objective and quantitative basis for future comparison of competing wood products and non-wood alternatives,
- An objective and quantitative basis for comparing systems which incorporate wood products to those systems which use alternative materials, for example, complex composite products or whole buildings,
- A method of comparing the environmental impacts of wood products from changed production processes,
- An up-to-date database for use with Life Cycle Assessments of Australian wood products and the buildings in which they are used,
- Facilitating communication of environmental information to customers and other stakeholders,
- Setting a benchmark for carbon sequestration in wood products, and
- Setting an industry standard for handling of environmental data.

1 INTRODUCTION

1.1 Background

Over the past decades there has been a growing recognition that consumption of manufactured products affects both resources and the environment. The production of a product impacts the environment, beginning with the extraction of raw materials, through processing, subsequent manufacturing, use and disposal, as well as all necessary transportation.

Such sustainability imperatives are starting to drive business decisions and government policies (e.g. Australian Government, 2007). As solutions are sought to environmental impacts, it is important to know how much energy, water or chemical has been consumed in manufacturing a product, and what greenhouse gas emissions or other emissions to the environment have been released in the process. The most obvious impacts for the forestry and wood products industry include the effects of forest harvesting, the release of greenhouse gases, impacts on water quality, and waste disposal (landfill or recycle). Governments are increasingly incorporating consideration of environmental impacts in policy decisions and are also increasingly holding product manufacturers accountable for their impacts.

There is limited verified life cycle information available on forestry and wood products internationally. LCI information for wood products is the least well defined in any current Australian LCI database.

Thus, wood products are at a distinct disadvantage compared to other products, such as steel and concrete, as there was no detailed Australian database to provide strategic insight for use in pro-active environmental marketing, process improvement, comparison for product substitution, and, importantly, supply of information for building evaluation tools. Building designers and material specifiers currently do not have quality information based on scientific methods to determine when wood is a superior or competitive choice.

1.2 Objective

The overall objective was to create the first national, rigorous LCI of representative Australian forestry and wood products to enable evaluation and benchmarking of the environmental impacts of wood products for comparison with selected competing or alternate products.

The LCI database covers the following categories of forestry and wood products: softwood plantation and native hardwood regrowth forests; softwood framing and hardwood timbers; veneer and plywood, and laminated veneer lumber (LVL); particleboard and medium density fibreboard (MDF); and glulam and engineered I-beams.

The LCI database for forestry and wood products aimed to be of high quality, contain a range of representative products, and be consistent, credible, and demonstrably independent. Practicalities such as focusing on a limited but representative range of wood products, availability of resources, and availability of data meant that many decisions were made on what would constitute a satisfactory LCI database. The content is compatible with international standards and with an Australian National Life Cycle Inventory Database (AusLCI) whose specifications were being determined concurrently (Woodard and Grant, 2008).

The underpinning principle was to obtain substantial industry input to the forestry and wood products LCI database to confirm the processes and values used in creating the LCI database of wood products. The target was to obtain data from those producing between them at least 50% of Australian production in the defined categories.

1.3 Scope

The data collection was up to the consumption phase for the wood products when sold to a consumer (known as a cradle-to-factory-gate study) as shown in the dashed box under "Manufacturing" in Figure 2. This provides an accurate database of Australian wood products for various users to examine a wood product and consider its production history. Most importantly, it provides industry with a reference of production practices and the ability to benchmark and monitor performance over time.

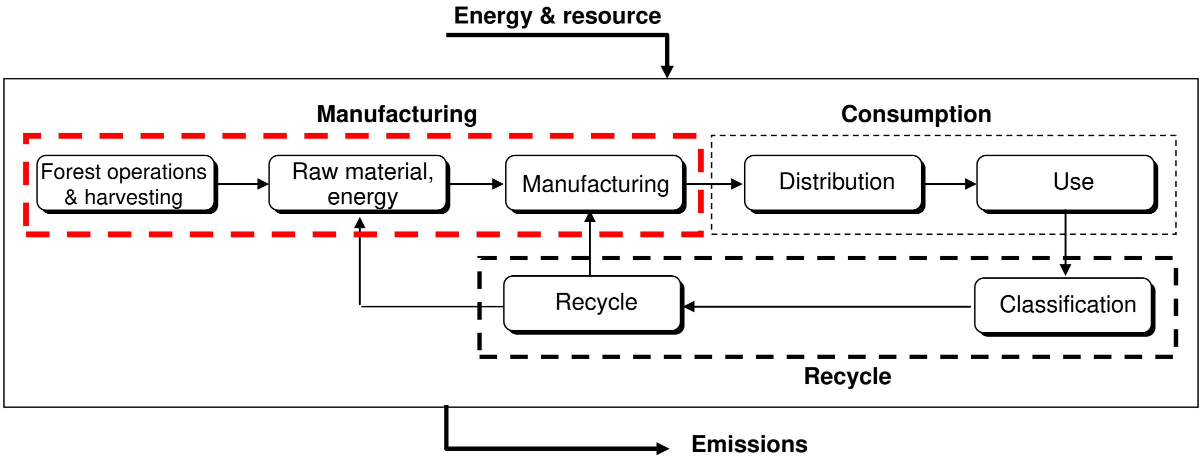


Figure 2 Process chain for life cycle analysis

A cradle-to-gate study is a practical way to collect data for a LCI database. Beyond this point, the useful life and maintenance requirements of wood products used in a building will depend upon a number of factors, including the exposure to weather and the use and type of preservatives and paints, all highly variable and not within the responsibilities of producers and manufacturing plants.

1.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is an objective process to evaluate the environmental burdens associated with a product or process over its life cycle by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements (Consoli *et al*, 1993).

"Life cycle" refers to all activities from acquisition of raw materials through to product manufacturing, and to the end use of these products and their eventual disposal or recycle, i.e. from "cradle-to-grave". Thus, Life Cycle Assessment quantifies the flow of materials and energy into and out of a system, as shown in Figure 3. The measures of environmental impact of the materials investigated are based on the outputs from the processes defined within the system.

1.4.1 Life Cycle Assessment framework

According to the ISO 14040 guidelines (ISO 14040, 2006) to the Life Cycle Assessment methodological framework, a Life Cycle Assessment shall include four elements: goal and scope definition, inventory analysis, impact assessment, and interpretation of results as shown in Figure 4.

The key component is the inventory (known as a Life Cycle Inventory) which contains the values of all the inputs and outputs for relevant activities undertaken to produce a product. It is this information which provides a quantitative basis for comparing wood products, their manufacturing processes and, most importantly from the forestry industry point of view, wood products performance against competitors who use other resources to create alternative products.

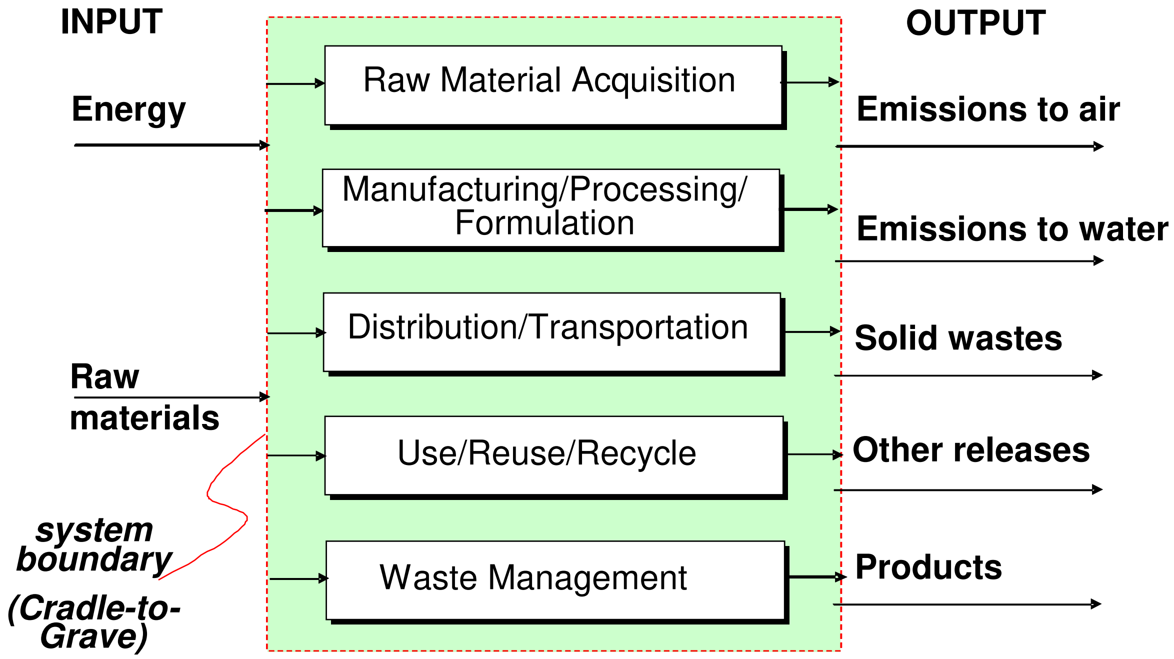


Figure 3 Life cycle assessment flow diagram showing indicative inputs and outputs

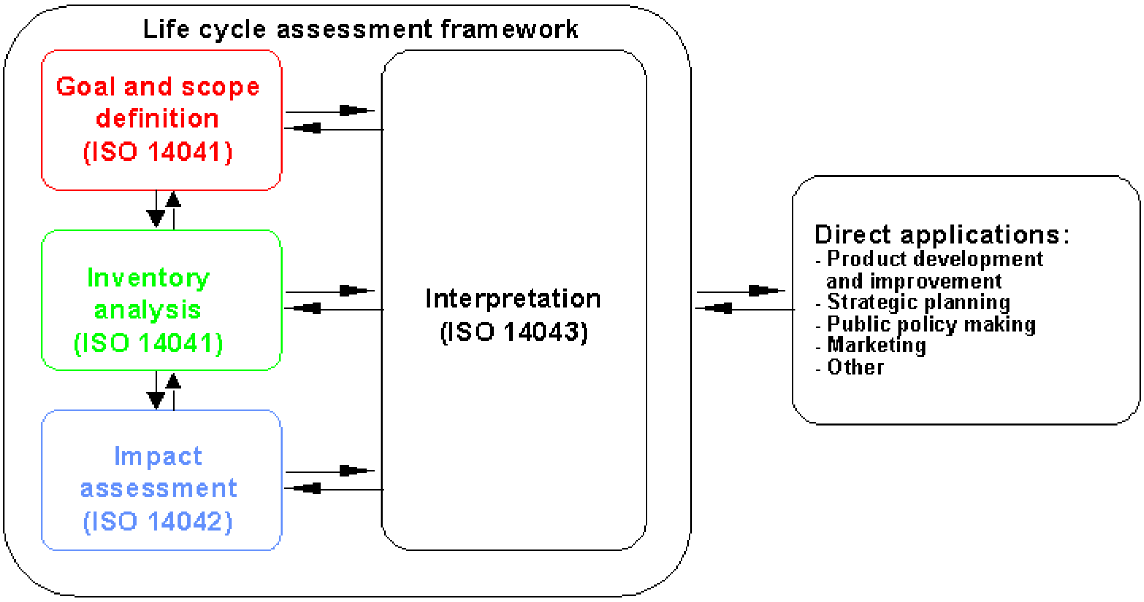


Figure 4 Life cycle assessment framework according to ISO 14040

The scope of a typical LCI only includes the inputs and outputs up to the factory gate, i.e. up to when a product is produced for a market as the subsequent inputs and outputs depend on the application of that product. In addition, the development of a thorough inventory results in the forestry and wood products industry benefiting through a more advanced understanding of the life cycle of its products and processes.

The results of the impact assessment step can be used in comparing environmental performance of products, identifying and improving environmental hotspots in the process or supply chain, and for environmental labelling and marketing of products.

1.4.2 Life Cycle Inventories

Over the past decade there has been an increasing application of Life Cycle Assessment to forestry and wood products. Countries in Europe and North America have completed detailed analysis of forestry and wood products in close collaboration with industry and timber research organizations (Wilson, 2005) as have Asian countries such as Japan (Tsuda *et al,* 2006). Organizations such as the Consortium for Research on Renewable Industrial Materials (CORRIM) in North America have worked extensively with a variety of stakeholders including the American Forestry and Pulp and Paper Association and the Engineered Wood Association to produce a sophisticated LCI of forestry and wood products in the United States.

Major international life cycle research studies conducted on the forestry resource (*i.e.* production of logs) and major wood products relate principally to the timber framing of houses and wood building construction (Seppala *et al*, 1998; Kakita, 2006). Guidelines have been developed for specific industries, an example of which is the American Forest and Paper Association user's guide for the US forestry industry (American Forest and Paper Association, 1996).

There are several national LCI databases in the Asian region; e.g. those of JEMAI (Japan Environmental Management Association for Industry), Japan; MoCIE (Ministry of Commerce, Industry and Energy) and MoE (Ministry of Environment), Korea; SIRIM, Malaysia and MTEC and MOI, Thailand.

One of the key distinctions between Australian and international LCI projects has been the lack of coordination, the minimal representation of industry and the limited detail of the final output in Australian databases, almost all of which are held in-house and not made public so that the data collection processes lack coordination and documentation is variable. In other countries, the process of effectively engaging industry has not only led to comprehensive LCI databases, but also the process of data collection has informed industry of the value and use of a LCI database. As a result the LCI database becomes a useable resource for industry.

The international experiences in developing LCI databases for a range of products show that it is a time consuming activity, particularly in obtaining adequate and consistent data. Many of the projects have taken years with consequent high costs of collection. The wood products industry in Australia was able to build on the international experiences in both determining protocols for data collection and LCI process modelling.

In Australia, there have been few Life Cycle Assessment studies undertaken for construction and packaging materials. Moreover, these studies did not so much include a full Life Cycle Assessment of wood or timber products but focused on embodied energy for timber products (e.g. Lawson, 1996). Todd and Higham (1996) reviewed Life Cycle Assessments of forestry and wood products. Some researchers have tried to compare environmental impacts of specific wood products with other alternatives using a Life Cycle Assessment method (Taylor and Van Langenberg, 2003). However, these Life Cycle Assessment and LCIs have had very limited work on the detail of forestry and wood products. The Cooperative Research Centre for Construction Innovation (Tucker *et al*, 2005) developed a building product LCI database for use with LCADesign, a software tool for eco-assessment of buildings direct from a 3D CAD including a database which contains some LCI data for forestry and wood products.

1.5 EXISTING DATA

1.5.1 CORRIM

The work of CORRIM (Consortium for Research on Renewable Industrial Materials) was of particular interest to this study, as they had recently (Wilson, 2005) completed a LCI of wood products in the United States, which had undergone an external critical review ensuring compliance with ISO14040 protocols. CORRIM agreed to cooperate with the Australian LCI of forestry and wood products which was beneficial to the development of the methodology of this study and provided opportunities to learn from their experiences, processes, models and methods.

CORRIM assessed the inputs and emissions from growing and harvesting forests in two regions of the USA, South Eastern United States (SE) and Pacific Northwest (PNW) regions (Johnson *et al*, 2005) and the manufacture of wood products from these two regions. The products assumed to be produced from each region included pulpwood, woodchip and saw (small diameter logs processed through specific sawmills to produce both woodchips and sawn timber) and sawn timber (larger diameter logs that produce a higher proportion of sawn timber) from the southeast and sawn timber only from the Pacific Northwest. The manufactured wood products were sawn timber, plywood, laminated veneer lumber (LVL), particleboard, medium density fibreboard (MDF), glulam and engineered I-beams, all of which are relevant to the Australian forestry and wood products LCI.

Data was collected via surveys which requested a range of detailed data including all production data such as inputs of materials, electricity, fuels, adhesive, etc. and all outputs including product and co-products, as well as emissions. All survey participants provided high quality data based on comparisons between plants, and mass and energy balances. The survey data, along with models developed earlier for the various wood residues used as raw material input to manufacturing, were used to construct LCI models for the various wood products. The burning of chips in boilers was addressed separately to obtain a better understanding of the process of obtaining heat from wood.

The analyses of the wood products were a gate-to-gate analysis (with the addition of raw material, such as logs and adhesive, transport) considering the impacts associated with manufacture, documenting all inputs and outputs and their impact. Primary data was collected through a survey of manufacturers and secondary data obtained for impacts associated with manufacture and delivery of such inputs as electricity and fuels, and adhesives. The data collected was averaged and weighted and modelled using the life cycle assessment computer software SimaPro. Although the system boundary was ‘gate-to-gate’, the details of the various product analyses were not identical, e.g. the plywood process was divided into six ‘unit processes’ whereas a single process or ‘black box’ approach was utilized for LVL.

CORRIM also developed a LCI database and modelled the life cycle environmental performance of renewable building materials in residential construction. Of most interest are the databases and reports developed for the various products (e.g. CORRIM, 2001, 2004, 2004a, 2004b, 2005). CORRIM is continuing further studies of forestry and wood products (CORRIM, 2008). The database later became part of the United States National LCI database supported by the National Renewable Energy Laboratory (NREL.)

CORRIM followed the ISO guidelines in developing a Life Cycle Assessment methodological framework for their studies, but found it is essential to provide very detailed information on every aspect of data collection and process modelling to ensure consistency, compatibility and credibility in meeting the objectives of a LCI database. Thus, the plan for developing a LCI database included a preliminary step where standards were set and strict guidelines developed. The development of the Australian LCI for forestry and wood products followed the same pattern.

1.5.2 Other international studies

LCI studies of forestry, wood products and processes are becoming more common around the world and range from very specific studies to general for inclusion in databases encompassing a range of manufactured products, e.g. the CORRIM results are incorporated into the NREL LCI database. Existing LCI studies of forestry and wood products were reviewed to identify sections of the LCI that have the largest impact on the LCI results. Existing national and international literature helped determine ways to reduce the scope of the project by focusing on data collection, for example, to determine where certain parts of the process give rise to 'hotspots', or processes and modelling decisions that have a large influence on the results. The following highlights those sources which have been helpful to the project.

- The United States LCI database (NREL, 2007) provides 'cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly.' ISO protocols are followed and the database has been independently reviewed and includes the CORRIM data along with data from many other industries in the United States.

- The United States Department of Agriculture (USDA) website provides United States forestry and wood information and includes the Wood Handbook - Wood as an engineering material. General Technical Report (USDA, 1987).

- A recent life cycle assessment study by Sonne (2006) investigated greenhouse gas (GHG) emissions from forestry operations in Douglas-fir plantations in the Pacific Northwest. The study investigated various management intensities and rotation ages and transport to the mill following harvest was not included in the study.

- The Environmental Resource Guide (ERG) is a United States guide detailing the environmental impact of building materials and is published by Wiley in conjunction with the American Institute of Architects. The assessment uses a simplified methodology and is targeted at material specifiers (Demkin, 1996).

- The Building Research Establishment (BRE) in the UK has undertaken extensive material database development including environmental profiles (Howard *et al*, 1999 and BRE, 2007).

- Nebel and Nielsen (2005) undertook a Life Cycle Assessment of roundwood logs from pine plantations in New Zealand and built upon an earlier study from Gifford *et al*. (1998). The study included nursery, forest establishment, forest management and harvest of the timber. Regional differences within New Zealand were also analysed.

- Several LCI studies in Sweden and Finland covered forestry (e.g. Karjalainen and Asikainen, 1996; Aldentun, 2002; Berg and Karjalainen, 2003; Berg and Lindholm, 2005a,b). Petersen and Solberg (2002) made an inventory of greenhouse gas (GHG) emissions and energy use over the life cycle of glulam and steel beams at the Gardermoen international airport outside Oslo.

- Many studies of Life Cycle Assessment have been undertaken in Germany covering a wide range of materials, including wood. Among the published work are product declarations (product category rules) conducted by AUB (Arbeitsgemeinschaft Umweltverträgliches Bauprodukt e.V.) (AUB, 2005).

- The Hong-Kong Housing Authority has done an extensive study of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) of building materials and components (Hong-Kong Housing Authority, 2005).

- Tsuda *et al* (2006) used Life Cycle Assessment to evaluate the environmental impact of a sustainable building which used local timbers in Japan. The environmental emissions were quantified for local glued laminated timber (Glulam) and they also compared environmental emissions between local glulam and imported products. Five different air emission gases (CO_2, SO_2, NO_2, CH_4 and N_2O) were considered.

- SimaPro, developed by Pré Consultants (Pré Consultants, 2008) is the Life Cycle Assessment software selected to model the results of this project. SimaPro is a widely used Life Cycle Assessment software in Australia and elsewhere in the world and has a number of large LCI databases included. The Australian component was created by RMIT.
- Boustead was the first computer modelling tool for LCI calculations and the model contains core data sets and process, raw materials and emissions data. (Boustead, 1995; Boustead, 2003; Boustead, 2007)

1.5.3 Australia

Australian LCI information has been less well developed and there are few sources to draw upon. Those sources which do exist are mostly confidential.

The NSW Department of Commerce (DoC) developed LCI operations for LCAid and prepared an LCI report (Hall and Janssen, 1997) based on Boustead (UK) and Forintek (Canada) data and methodologies. The data was 'Australianised' although it still may be more reflective of international processes. Knowledge of LCADesign (Tucker *et al*, 2005), LCAid's successor, and developments of data collection, methodology and database, aided the process. The National Pollution Inventory (NPI) which is a database of substance emissions in Australia (Environment Australia, 2002) provided data on emissions from manufacturing plants including those producing wood products.

There is no existing lifecycle inventory for plantation and native hardwood forestry in Australia. However, there has been work on various aspects of wood products (e.g. Ximenes and Gardner, 2004). There is a lack of published LCI information relating to sawmill products in Australia.

In 2004, the Laminex Group commissioned the RMIT Centre for Design to undertake a Life Cycle Assessment of all major Laminex Group products at each of the production locations in Australia and New Zealand (Grant, 2005). This study showed significant variation based on the amount of biomass used at each location and the electricity grid supplying the production site. Adhesives had a small but significant effect on environmental impacts of different products.

Thus, Forest and Wood Products Australia (FWPA) initiated this project to establish a detailed LCI for wood products to fill a need for the wood products industry and to set a standard for other Australian industries to follow.

1.6 Starting point

The starting point for the Australian LCI database was that developed by CORRIM for the United States wood products industry. CSIRO developed a strong working relationship with CORRIM and, significantly, CORRIM agreed to provide CSIRO with all reports describing protocols, processes and reviews as well as information on process models for manufactured wood products. However, CORRIM did not have a model that was satisfactory for Australian forestry production systems and this was an area that required additional attention for data collection. Nevertheless, this was an invaluable relationship and source of information and saved person-years of work for the preparation of this LCI database.

The Australian LCI of wood products only considered the production of wood products up to the completion of the manufacturing stage (cradle-to-gate study) and included forestry production systems. This provides a LCI database which can be used for analysis by others.

The format of data developed in this project for database documentation conforms to ISO 14048 and other emerging standards in Europe for consistency with global datasets. FWPA required that the LCI results of this project be available and compatible with the proposed national LCI database, AusLCI, currently being developed for Australian products.

2 INDUSTRY COVERAGE AND DATA COLLECTION

2.1 Range of forestry and wood products

While the initial aim was to develop LCIs for generic wood products, the detailed data was sufficient to provide information on common categories of the generic products. Table 9 shows the original categories of products and the expanded (more specific) range of products actually developed for the Australian forestry and wood products LCI database as well as the final coverage for each category of forestry and wood product.

Table 9 Products in the LCI database and coverage of Australian production

Category	Products	Coverage of Australian production (approx %)
Logs – Softwood	Peeler log, High quality saw log, Low quality saw log, Chips	50
Logs – Hardwood	Peeler log, Saw log	22
Sawn timber – Softwood	Rough sawn green timber, Rough sawn kiln dried timber, Planed kiln dried timber	40
Sawn timber – Hardwood	Rough sawn green timber, Rough sawn kiln dried timber, Planed kiln dried timber	30
Plywood	Interior Plywood, Exterior Plywood, Formply, Tongue and Groove Flooring, Structural Plywood (each 3 thicknesses)	90
Laminated veneer lumber (LVL)	LVL (3 thicknesses)	60
Particleboard	Raw and Decorated (each 3 thicknesses)	64
Medium density fibreboard (MDF)	Raw and Decorated (each 3 thicknesses)	92
Glued laminated timber (Glulam)	Pine	55
I-beams	Oriented strand board (OSB) web and pine flanges, Plywood web and LVL flanges	65

2.2 Australian production

2.2.1 Plantations

Australia has about 1.7 million hectares of forest plantations that produce wood products (Table 10). That area is comprised of 1.0 million hectares (57%) coniferous (softwood) species and 0.7 million hectares (43%) broad-leaved (hardwood) species (Parsons *et al.* 2006). Softwood plantations have been established in all States except the Northern Territory. *Pinus radiata* is the predominant species planted across southern Australia, while *P. carribea* and *P. elliottii* or hybrids are planted in Queensland. In Western Australia, *P. pinaster* is also grown, while in Queensland native hoop pine is also grown.

The area of softwood plantations has been relatively stable while the area of hardwood plantations has been increasing steadily since the mid 1990s. The areas in each State and region are shown in Table 10. Hardwood plantations are primarily being grown to produce woodchips and not included in this LCI.

Table 10 Australian plantation estate by State/Territory in 2004

State	Softwood (ha)	Hardwood (ha)	Total (ha)	Total (%)
Australian Capital Territory	9,500	0	9,500	1%
New South Wales	273,606	55,196	328,802	19%
Northern Territory	2,239	14,090	16,329	1%
Queensland	186,033	37,496	223,529	13%
South Australia	124,163	42,341	166,504	10%
Tasmania	71,600	155,500	227,100	13%
Victoria	218,412	164,724	383,136	22%
Western Australia	104,480	270,813	375,293	22%
Total	**990,034**	**740,161**	**1,730,195**	**100%**
Proportion of total	56.9%	42.6%	100%	

Source: Parsons *et al* (2006).

In regions which have achieved a critical mass of plantation resource, such as the Green Triangle in south eastern South Australia and western Victoria, the Murray Valley in north eastern Victoria and the south western slopes of New South Wales, there is an integrated industry which value adds to all plantation products. These diverse sources required separate analysis of seven regions.

2.2.2 Native forests

Of Australia's 163 million hectares of native forests, there are 11.4 million ha of publically owned forests and 40 million ha of privately owned forest, managed for a range of purposes including wood production (ABARE, 2007). The primary areas of native are located in Tasmania, Victoria, New South Wales and south west Western Australia covering a wide range of eucalypt species. The total area includes reserves, buffers, and low productivity forests. Thus, only a fraction is actually available for harvest. Over 70% of forests identified as "old growth" in areas covered by Regional Forest Agreements are reserved from timber harvesting. However, some old growth forests will continue to contribute to timber supplies in the short to medium term in Tasmania.

2.2.3 Logs

Between 2001 and 2007, softwood plantations contributed 54% of the total wood harvested and 72% of total saw and veneer logs (ABARE 2007, Table 11). Hardwood plantations contributed 10% of total production with 93% of this in the form of pulplogs, most of which were exported as woodchip. Native forests contributed 36% of total wood production, with 35% of this as saw and veneer logs and most of the remainder exported as chips.

Table 11 Average annual Australian log harvesting from 2001-07

State	Softwood plantations (million m^3)	Hardwood plantations (million m^3)	Native hardwood forests (million m^3)	Proportion of total (%)
Saw and veneer logs	9.0	0.2	3.3	48%
Pulplogs	4.8	2.4	6.0	50%
Other logs	0.4	0.0	0.2	2%
Total	**14.2**	**2.5**	**9.5**	**100%**
Proportion of total	54%	10%	36%	

Source: ABARE (2007) Forest and Woods Statistics

2.2.4 Sawmills

The product mix from both hardwood and softwood native forests and plantations in NSW (Forests NSW, 2006, 2006a) shows that the main product use from softwood sawlogs is house framing which represents 73% of the sawlog product mix. The main product from hardwood sawlogs is floorboards which represent 48% of the sawlog products, followed by house framing 15%, pallets 10%, fencing/landscaping 9% and dry structural 8%. Joinery/furniture, decking/panelling and high strength structural together account for about 10% of hardwood sawlog products.

While the importance of particular products for softwood has remained much the same over the past decade, the same is not true for hardwood sawmill products. Most notably, floorboards have become the main hardwood sawmill product, doubling its proportion of the product mix over the past ten years. In contrast, house framing and dry structural are now *relatively* less important in the hardwood product mix.

Australian production of sawn hardwood has been declining over many years from a peak of 2.65 million m^3 in 1968 to 1.6 million m^3 in 1995 and in 2004 was just over 1 million m^3 (ABARE, 2006).

IBIS (IBIS 2003, p10-11) notes that the industry structure is changing from small mills to large mills. In addition, industry associations have observed that the number of sawmills has decreased: "In 1975 we had more than 270 sawmills processing native timber. In 2005 there were 75" (VAFI, 2007).

2.2.5 Veneer, plywood and LVL

The logs for plywood and LVL are sourced from both hardwood and softwood resources, with Australian forests accounting for 100% of the softwood and 60% of the hardwood (IBIS, 2003). The vast majority of the logs for veneer, plywood and LVL production are from established Australian softwood plantations of Radiata and Hoop Pine, with a small percentage being obtained from other forests. Hardwood for plywood products is sourced in Australia from native forest with small quantities from eucalypt plantations.

Plywood is being used for a far greater range of applications with the main products being interior plywood, exterior plywood, formply, tongue and groove (T&G) flooring and structural plywood. Marine plywood (which is not typically a construction material) and other plywood products, such as blockboard, sliced fancy overlay, bridgewood, and noise barriers, have a very small market share, making up less than 5% of total production. Table 12 shows the plywood product market shares as determined from mill surveys.

Table 12 Plywood products market shares

Category	Product	Volume (m^3)	Production share (%)
Interior Plywood	Interior A Grade	4775	4.2%
	Paint Grade	23	
	Paper Overlaid	500	
	Bendy Ply	44	
Exterior Plywood	A Bond	1977	1.9%
	B Bond	500	
Plywood Flooring	T&G	22548	17.6%
Marine Plywood	Standard	1016	0.8%
Formply	A Bond	25536	33.3%
	B Bond	17200	
Structural Plywood	BB	9696	38.8%
	BD	64	
	CD	24032	
	DD	6128	
	Cladding	8700	
	Strip Floor	1000	
Other Products	Blockboard	17	3.4%
	Sliced fancy overlaid	93	
	NS	1328	
	Bridgewood	530	
	Ezyshield	1500	
	Bracing	864	
		128071	**100.0%**

Source: Information collected from mill surveys

Only one manufacturer produces hardwood plywood, accounting for approximately 8% of the total amount of plywood produced. Some of the structural plywood produced by other manufacturers has hardwood cores.

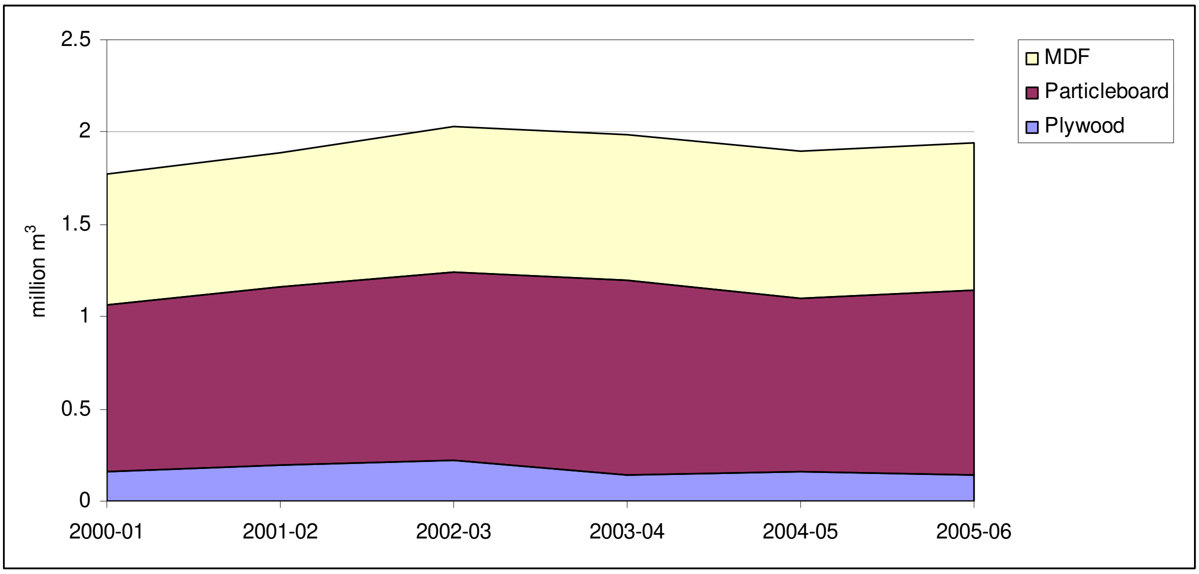
The biggest plywood mills are based on plantation softwood resources in Queensland, Victoria and South Australia. Over two-thirds of the total Australian production is by two companies, who are also major sawn softwood producers.

The gap between production and consumption is being met by imported plywood. The plywood and LVL industries do not import logs for production. However, some mills do import veneer, particularly specialty face veneers. Some mills are beginning to import plywood products which they may finish, or simply sell as their own product. Domestic demand for plywood exceeds production capacity in Australia with the deficit of 28.8% (share of domestic demand) being made up by imports. Imports of plywood are principally sourced 38.5% from New Zealand, 29.2% from Indonesia and 15.5% from Malaysia. Veneers for making plywood are also sourced predominately from Malaysia (15.2%), New Zealand (51.9%), Philippines (11.0%) and the US (5.5%) with other countries contributing small amounts (less than 3%) (ABARE, 2006, Table 36 Imports of veneer, 2005-2006).

2.2.6 Particleboard and MDF

Particleboard is manufactured from forest thinnings, peeler cores, and from sawmill residues including off-cuts, planer shavings and sawdust. These are chipped and flaked into particles, and then sprayed with a liquid adhesive. Fibre for MDF manufacture requires chips, so the raw material requirements are more stringent for MDF compared to particleboard. Thinnings and slab wood are chipped, with the chips then being heated to soften them before being torn into fibres.

Particleboard manufacture dominates domestic wood panel production, where it accounts for around 50 percent (1 million cubic metres) of total wood based panel production in 2005-06 (Figure 5). Growth in particleboard production increased at an average annual rate of 2.3% over the period 2000-01 to 2005-06. MDF production has been growing at a similar average annual rate over the same period and now accounts for 41 percent of wood based panel production (ABARE, 2007).



Source: ABARE 2007, ABARE 2003

Figure 5 Australian MDF, particleboard and plywood production (million m^3)

2.2.7 Glued laminated timber (glulam)

Total annual production of glued laminated timber (glulam) is estimated to be 48,100 m^3 in Australia (Table 13).

Table 13 Glulam production in Australia

State	Production	
	Amount (m^3)	%
Queensland	19600	41
Victoria	16000	33
Tasmania	12500	26
TOTAL	**48100**	**100**

Note: Estimated figures from GLTAA

2.2.8 Production of I-Beams

Based on the 2005 figures, I-beam production capacity is estimated to be about 25 million lineal metres in Australia. Considering new facilities in Western Australia, the production capacity would currently be more than that amount. Since 1997, when large scale production of I-beams began in Australia, the production has grown to almost 6.7 million lineal metres in 2004. Production of I-beam in Australia is shown in Table 14. This production is roughly 30% of the production capacity.

Table 14 I-Beam production in Australia*

State	Production	
	Amount (Lm*)	%
Queensland (QLD)	2,000,000	27
South Australia (SA)	3,480,000	46
Western Australia (WA)	2,000,000**	27
Others	-	-
Sum	7,480,000	100

*Lineal metre **estimate only

2.3 Data collection

Survey forms identifying all required data were developed in collaboration with relevant industry input from each of the five areas: forestry, sawmills, veneers and plywood, particleboard and MDF, glulam and engineered I-beams. The form, size, scope, location, operation and products of each industry component were different in each of the areas studied.

From a comprehensive list of Australian forests, sawmills and wood product manufacturing plants, a list of the industry providers of forestry and wood products who would be sufficient to achieve a target of 50% of Australian production was drawn up and approached for participation in the surveys. Typical forests, mills and plants were visited for visual inspection, initial data collection and identification and understanding of processes.

Seven case study regions – covering softwood plantations in the five States of Australia and hardwood native regrowth forests in three States of Australia became the representative sources of forestry data.

Because of the large number and varying scale of sawmill operations, a sampling procedure was set up to capture data from as many as possible of the large sawmills (a total of 22 softwood mills and 66 hardwood mills) using detailed data surveys. A simplified data form was sent randomly to a large number of the small sawmills to ensure that data from a full cross section of sawmills were included.

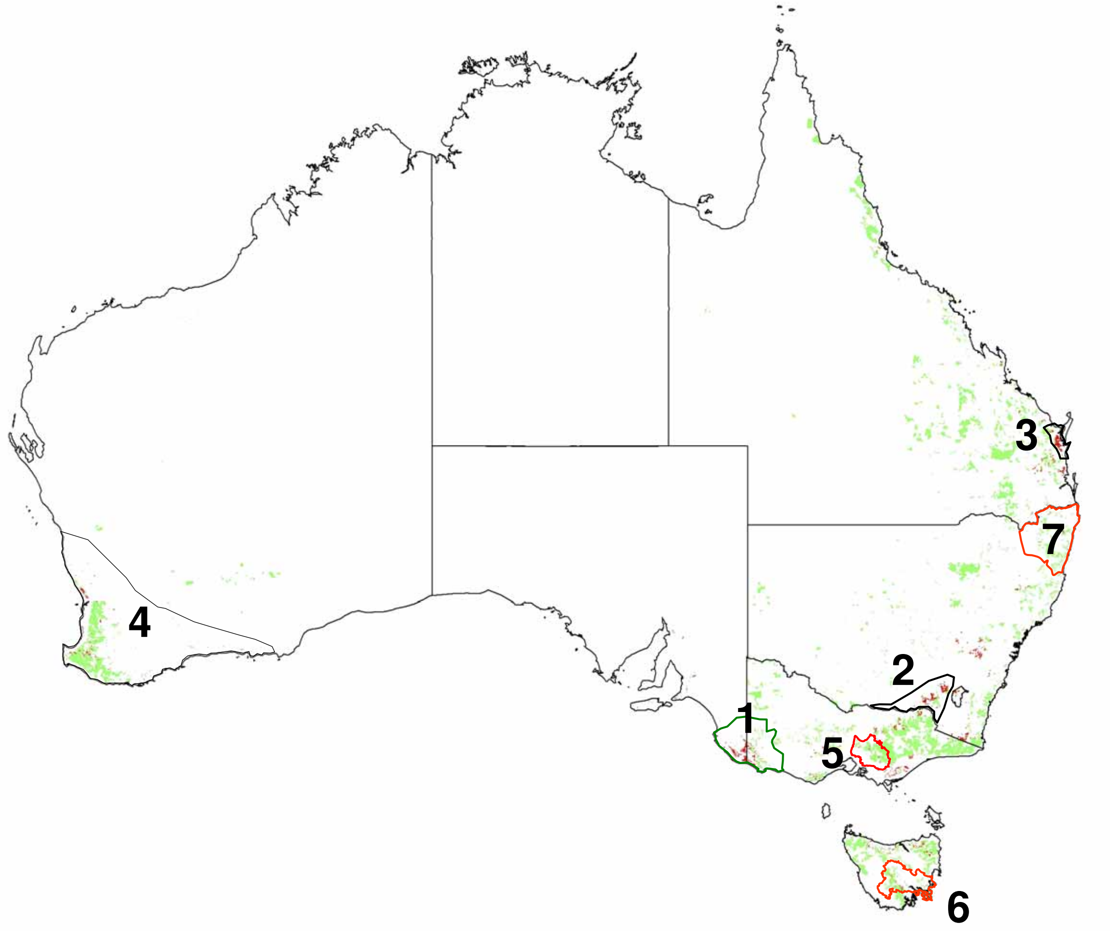
For the remaining plants manufacturing wood products in Australia, in any one category, there are less than ten producing almost all of the production in Australia so plants producing approximately 80% of Australian production were approached. Where clear differences in processes among the competing plants could be identified, effort was made to include representatives of each identified type. Cooperation levels were generally very high and some very detailed data was made available thus ensuring a thorough understanding of the processes, their inputs and outputs and comprehensive maps of the processes.

Data was collected by a combination of literature review, site visits, survey form and direct contact with those experienced in Life Cycle Assessments. Data collection was primarily focused on the surveying of industry participants. Site visits and contact with industry people were required in all cases. The surveyed data was crosschecked to ensure the responses from industry personnel were correctly entered before modelling was done. Also, the collected data for each of the products was compared with others (such as CORRIM data) to determine whether the collected data was reasonable.

Data confidentially was maintained at all times with only the individual researcher being responsible for collecting and managing an individual manufacturer’s data. Once validation was complete (outliers, missing data etc.), the process data was averaged based on weightings by production value. When requested by individual manufacturers, their LCI and environmental performance data on their processes was returned together with the industry average.

2.3.1 Case study forestry regions

Seven forestry case studies were covered in the current study as shown in Figure 6.



1. Radiata pine plantations - Green Triangle;
2. Radiata pine plantations - Tumut/Tumbarumba region of NSW (i.e. key softwood growing region of the Murray Valley);
3. Slash/Caribbean pine plantations - SE Queensland;
4. Radiata/maritime pine plantations - SW WA;
5. Regrowth native forests - Central Highlands of Victoria;
6. (Largely) regrowth native forests - Tasmania.
7. Regrowth native forests - north coast of NSW;

Figure 6 Map of Australian hardwood and softwood native forests and plantations showing the four plantation softwood (dark green) and three native hardwood (red) case study regions

These regions cover about 48% of total plantation softwood production and approximately 68% of total native hardwood production across Australia for the period 2005-08 (Figure 7). However, not all of the areal extent of each region was covered by the case study in that region. This reduced the volume of total sawlog production covered to approximately 20%.

Most data were collected directly from forest owners, managers and contractors by means of surveys and interviews. The coverage of the surveys corresponded to National Plantation Inventory regions (Green triangle and WA), Regional Forest Agreement areas (NE NSW and Central Highlands Victoria), or defined management regions or districts (e.g. Derwent District for Tasmania, Fraser Coast for south east Queensland). The temporal scope consisted of data covering the period 2001-06 for management inputs and wood production. Detailed information for harvesting, haulage and other contractor operations generally covered the period 2005-06.

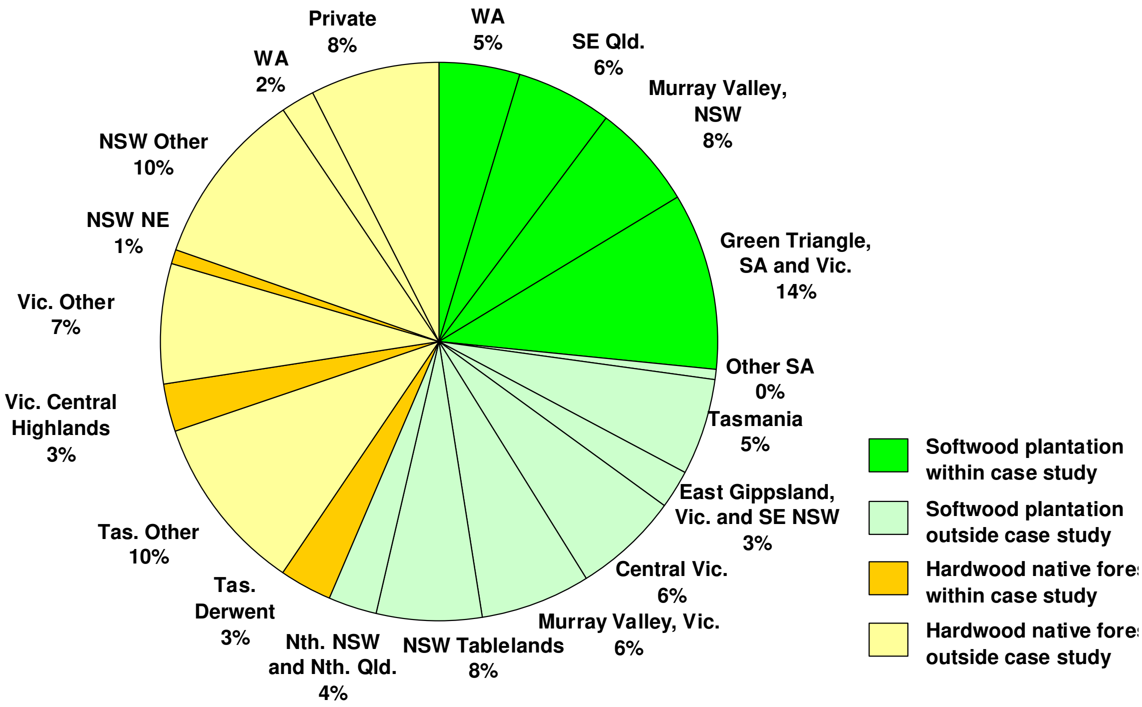


Figure 7 **Average percentage contribution by region, to Australia's annual wood supply from plantations and native forests showing proportion covered by survey. Source: ABARE (2007), Forests NSW (2007), Forestry Tasmania (2007), FPC (2007), Parsons *et al.* (2006) and VicForests (2007).**

Survey forms were specifically tailored to match the activities of each data provider. Those used for forest owners/managers covered a wide range of activities including seed/seedling production, establishment practices, chemical and fertiliser application, roading, wood production, as well as major contractors. Information on total vehicle and machine usage and fuel consumption was collected separately and allocated to different activities by the forest owner/manager in terms of percentage of total use. Where activities were carried out jointly by contractors, the forest owner was asked to estimate the proportion of the activity (based on area or machine usage rates) undertaken by the contractor. Similarly, where activities such as fuel reduction burning or fire control were undertaken outside the area covered by the case study, usage of machines was allocated to the area managed for wood production on a pro-rata area basis.

Contractor survey forms focussed on inputs and outputs for the activities within the forest estate undertaken by each contractor. These included site preparation, aircraft operation, road construction, harvest and haulage. Data included vehicle and machine usage, fuel and lubricant consumption, replacement parts (including tracks, filters and tyres), and productivity, truck load weights and haulage distances. In addition, process descriptions were obtained indicating which machines and vehicles were used for which operations. To help validate the estimates of fuel consumption, data on total annual machine hours, vehicle kilometres, fuel usage and amounts of product harvested was also requested. Where available, these reference data were used to calibrate the individual machine productivity and fuel consumption rates per unit of wood production. Although the there were typically a large number of contractors involved in forest operations in each case study region for softwood plantations in particular, generally 60-90% coverage was achieved.

2.3.2 Softwood and hardwood sawmills

Data was collected and reported separately for softwood and hardwood mills. A literature review was conducted as part of this study and used to design surveys to capture important material and energy flows, modelling issues as well as provide data for evaluation of results.

A large effort was undertaken to capture data from the sawmills. Sixty six large hardwood mills and 22 large softwood mills were contacted and sent the survey. Each mill was contacted a number of times and offered support for data collection. A log of all contact was maintained and approximately 500 phone calls and many emails and faxes were sent as part of the data collection effort. A number of sites visits were undertaken to mills in New South Wales and Victoria.

Data was collected for eight softwood mills and represents approximately 40-50% of softwood production in Australia. The coverage in Australia includes mills from Queensland, NSW, Victoria, South Australia and Western Australia.

Usable data was collected for 18 medium to large hardwood mills. The response rate was about 22% and was variable across Australia. This represents approximately 20-30% of production. The response rate was increased through the use of the simplified survey. The coverage in Australia includes mills from Queensland, NSW, Victoria, Tasmania and Western Australia. Approximately half of the mills were from NSW and Victoria.

The percentage captured was estimated using the best available population frame from ABARE. However, the population frame is almost a decade old and the hardwood industry in particular has undergone significant change over this period. The survey thus focused on larger producers, which follows the industry trend. As a result, the estimate of the volume of production captured is likely to be conservative. The survey captures a significant percentage of industry production but was not a statistical sample and may be skewed towards larger producers, especially for the hardwood industry.

2.3.3 Plywood and LVL mills

In 2003, a total of 38 Australian plywood mills being owned by 23 distinct organisations were identified (IBIS, 2003). By 2007, there were only a small number of plywood and LVL mills remaining - 8 plywood and 2 LVL mills. The small sample size and data confidentiality required that final results could not distinguish between mills. Issues and hotspots determined by CORRIM, such as regions, wood types, products, and energy, and additional issues identified in the literature review were pertinent to address. Therefore, it was decided to undertake an analysis of as many as possible of the mills to determine the differences and similarities between the mills which might make a difference to the inventory data.

The factors taken into account when both selecting plants for inclusion and for checking the impacts of such factors were:

- Production capacity (small, medium, large),
- Volume of production,
- Percent of Australian total production,
- Product range (commodity, commodity and niche, hardwood niche, high quality niche),
- Location (New South Wales, Queensland, South Australia and Victoria),
- Proximity to forest (in forest, <100kms, >100kms),
- Technology (old, mainly old, new support, upgraded, automated, new),
- Energy, sources (gas, waste wood, co-generation), and
- Log type (Radiata Pine, Hoop Pine, Slash Pine, Eucalypt).

The mills surveyed had to produce a representative amount of Australian plywood. It was no use surveying six mills, if the other two produced 60% of the total Australian production. A representative selection of products with significant market share was included as the small mills often had greater product range or niche market products while the big mills produced the commodity products such as structural plywood or formply.

A geographical cross-representation of mills was analysed to take into consideration the variety of regional issues, such as proximity to forests, as the log inputs are significant to plywood production and transportation is therefore an important impact issue.

Technology differences were investigated as, while the processes may still be the same, the boiler efficiencies, heat recovery, waste reduction and recovery, may be improved with modern technology. Since energy has the potential to make the most difference to the LCI, it was necessary to investigate different energy types and adequately understand the cross-representation of energy use. Wood waste is the most predominant fuel for drying furnaces and hot pressing but gas and co-generation are also used. There are many log types used in the production of plywood and the significance of these differences (whether relating to issues of region, transportation, waste, hardwood and softwood etc.) was addressed.

To take into consideration the major producers and a selection of smaller producers, while leaving some mills excluded for future checks, the mills studied were one large plywood mill and one small plywood mill in Queensland; two small/medium plywood mills in New South Wales; one large plywood mill in Victoria; and one large plywood mill in South Australia. The largest two mills, which produced more than 50% of plywood, or the top two organisations (three mills) could have been validly selected as they covered nearly 65% of the Australian production capacity. The included mills contributed to more than 90% of Australian plywood production. The only hardwood plywood mill in Australia was included to investigate the impact use of hardwood veneer makes on the results and provide information on hardwood plywoods.

There are only two LVL mills in Australia. Because the LVL manufacturing process turned out to be very similar to that of plywood, all but the last stages were common and thus plywood and LVL used the averages for both in the common stages.

2.3.4 Particleboard and MDF plants

There are currently eight particleboard plants in Australia, four of which are owned by one company. There are no recent data on the output capacity of the individual particleboard and MDF plants available to the researchers. The output capacity reported by Plantations Southeast appears to refer to the period 1996-97. The actual total Australian production in 2006-07, as reported by ABARE (2007), is 20% higher than the 1996-97 capacity. The coverage of the plants that have provided data is 79% of the total particleboard production in Australia.

There are currently only four MDF plants in Australia, two of which are owned by one company. The actual total MDF Australian production in 2006-07, as reported by ABARE (2007), is 9% lower than the 1996-97 capacity. As reasons for the lower output ABARE points at the closure of the MDF plant in Bell Bay (150,000 m^3 output capacity) and a general decline in wood panel consumption of 17% in Australia in 2006-07, compared to the previous year. Based on these figures the coverage of the three plants that have provided data is 91% of the total MDF production in Australia.

Willingness to participate in the project and availability of data were of vital importance as any mill surveyed would be critical to the data quality given the small range of mills. The mills had to commit to both collecting and providing data which is an onerous task, particularly in smaller mills where day-to-day operation is the focus (Mitchell, 2004).

All mills within the sample set were members of the AWPA (Australian Wood Panels Association Incorporated). The assistance of the AWPA allowed entry to discussion with mill executives and helped disseminate the significance of the project to the particleboard and MDF industry. Once the level of involvement was ascertained to be appropriate for the project requirements, the mills were engaged to collect data.

Given the necessary understanding of industry processes, determining data required was an iterative process. The knowledge obtained during initial data collection processes lead to the refinement of data requirements. The initial data requirements were based on RMIT's LCI data surveys, other data surveys, data collected previously in the particleboard and MDF industry and data considered relevant for our own knowledge of the industry. Data requirements included information on inputs and outputs (such as raw materials and ancillary materials; energy and water; and waste and emissions); transport, land use and plant and equipment.

2.3.5 Glued laminated timber and I-beam manufacturing plants

For the survey to collect data, manufacturing plants for glulam in Queensland, Victoria and Tasmania were primarily screened and identified based on their production capacity and representativeness of the industry. Four manufacturing plants participated in the survey which covers 89% of the annual production of Victoria and 58% of the annual production of Queensland. Tasmanian production was not included in this study. Total annual production from the manufacturing plants surveyed was 25,530 cubic metres, which approximately covers 53% of the total Australian production.

I-beam manufacturing plants in Australia were selected based on the I-beam production capacity and representativeness. Two manufacturing plants were considered in the survey to provide data on I-beam and co-production, raw materials, ancillary materials, energy consumption (electricity, LPG, gas, etc) and corresponding emissions. The manufacturing plants that participated in the survey produce approximately 73% of the total I-beam production in Australia.

The small number of mills meant that each was approached on an individual basis and was visited by members of the research team. A survey form was developed as a guide to obtaining the required information.

3 DEVELOPMENT OF THE LCI DATABASE

3.1 Guidelines, documentation and quality assurance

An essential first step in developing the LCI database was to set up the process before gathering any data for the LCI. There are established guidelines for creating a LCI database in the form of the ISO 14040 series of standards (ISO 14040, 2006) including ISO 14044 Life cycle assessment — Requirements and guidelines (ISO 14044, 2006) and ISO/TS14048 Life cycle assessment — Data documentation format (ISO 14048, 2002). ISO 14044:4.2.3.1 states that the scope of a LCI study shall specify the following items: product system to be studied; functions of the product system; functional unit; system boundary; allocation procedures; data requirements; assumptions; limitations; data quality requirements; type of critical review, if any; and type and format of the report required for the study.

Documents setting out the standards and guidelines for the whole procedure were prepared, from scope of the LCI to modelling the processes to provision of the LCI data. Decisions were made on: selection of products, selection of plants (or manufacturers), contacts with industry people, meetings (workshops) with industry people, selection of unit process (unit flow), input/output parameters, and construction of standard process flowcharts. This minimum set of requirements for the conduct of the LCI study was necessary to ensure data quality, consistency, reliability, transparency and documentation of the results across the various components of the project.

These guideline documents on LCI and quality assurance procedures were deliberately practice oriented and conform to the ISO standards (Tharumarajah, Grant *et al*, 2007 and Tharumarajah, Park *et al*, 2007).

3.2 System boundaries

The system boundary determines which unit processes shall be included within a LCI. The selected system boundaries influence the results and what conclusions can be drawn from a certain study. Thus, when LCI data is collected for a product, system boundaries must be clearly defined, i.e., which, and to what extent, activities within as well as outside the product are considered. Also, the system boundaries were selected in a consistent way across all the Modules[1] and were well documented.

The life cycle stages as defined by the scope of the project were grouped in Modules (shown as dotted lines) as follows (see Figure 8):

- Softwood and hardwood logs (from regrowth native forests and softwood plantations)
- Sawmilling of softwood framing and hardwood timbers
- Veneer, Plywood and LVL (laminated veneer lumber)
- Particle board and MDF (medium density fibreboard)
- Glulam and Engineered I-beams

The boundaries for each product group module under study in this project were separately and more narrowly determined with the softwood and hardwood logs covering cradle-to-gate (supply of logs) while others model from gate-to-gate. Using these Modules, it was possible to construct cradle-to-gate systems necessary to model the LCI of manufactured wood products. It is also possible to construct an elaborate cradle-to-gate LCI for products that use these products as inputs (such as furniture from wood) by combining the individual LCIs.

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[1] The project was run as six independent groups (called Modules A to F) with Module A setting standards and guidelines for developing the LCI and co-ordinating the activities of the other Modules.

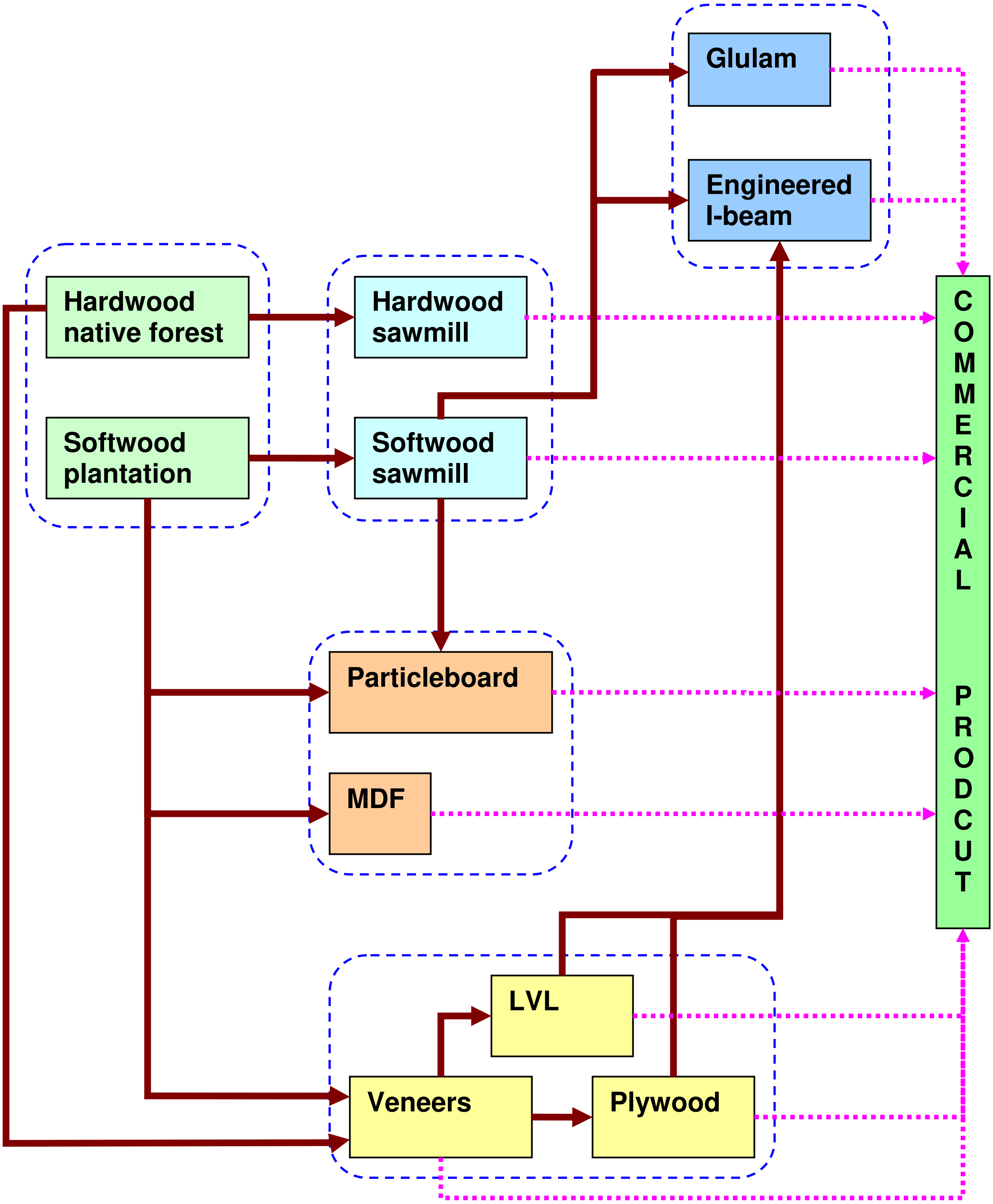


Figure 8 System boundary of LCI product groups and inter-links

A separate transportation process is required to connect the flow of product materials. This made it easier to update changes in supply chain geography and also provide the flexibility for a user of the LCI data to specify his/her modes of transport and distances.

An example of the detailed specifications is the system boundaries as shown in Figure 9. A quality assurance plan was put in place and data documentation spreadsheets developed in spreadsheet form with accompanying checklists to ensure documentation met ISO standards.

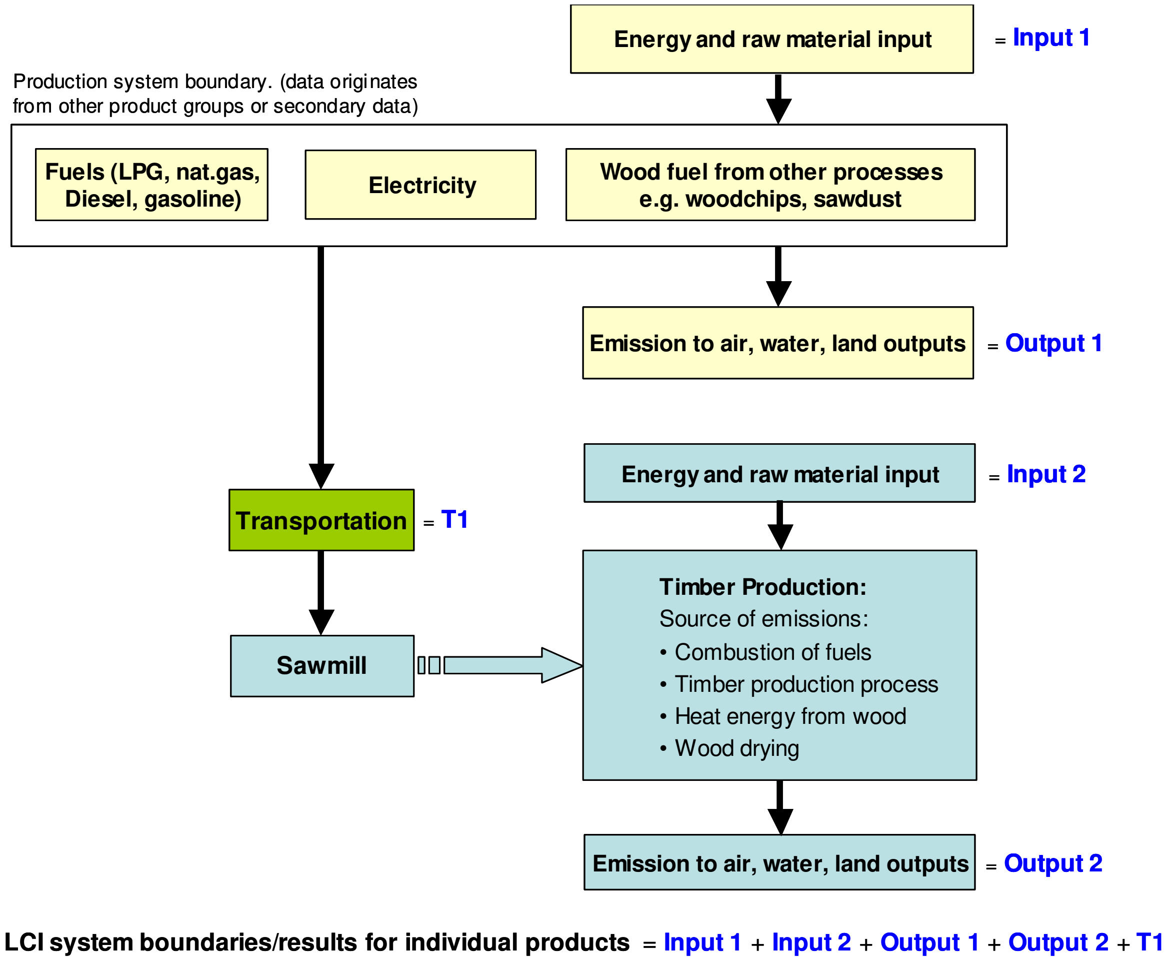


Figure 9 System boundaries for individual processes in the LCI Timber project

The raw materials are the materials obtained directly from the environment. The inputs between the LCI boundary and the product group boundary are common or pre-defined processes which can be called upon by any of the inventory product models. Common processes model the environmental emissions associated with inputs from, and outputs to, processes that are not an integral part of the industrial system under study. The common processes include logs from forests, adhesives, imported products and materials (adhesives and wood products such as oriented strand board), energy supplies (electricity, gas, etc), transport modes (ships, aircraft, rail, trucks, cars etc) and equipment.

The output products include the main product, by-products and wastes. A product system (i.e. the unit processes therein) was modelled in such a manner that inputs and outputs at the boundary are elementary flows or environmental emissions, and product flows.

In this study no cut-off rules were applied, i.e. all available data on inputs and outputs were utilised, no matter how small their contribution may be.

As is LCI practice, the following components of the unit processes were excluded from the study:

- All contributions from production of machinery and infrastructure,
- Human labour,
- Manufacturing of transportation vehicles, and
- Transportation of packaging parts from production site to manufacturing site of forestry and wood products.

3.3 Unit processes

ISO 14040 (ISO 14040, 2006) defines a unit process as the “smallest portion of a product system for which data are collected when performing a life-cycle assessment.” Thus, the choice of a unit process is self-defining – if the data is available at a machine level, the machine is the unit process or alternatively, the data is at a factory level, the factory is the unit process. A model of an entire supply chain will generally contain data for unit processes at various physical scales. Provided the system boundary remains intact and all flows across the boundary are correctly accounted, then a wide variety of scales of processes can be consistently and appropriately measured.

The unit process is the building block of the process tree that contains environmental data, as well as data of all necessary material, energy, transportation, etc., inputs and all emissions. The unit process is devoted to the **one reference unit** (it can be 1 kg; 1 tonne; 1 m^3; etc) of the process output. The unit process can have multiple product output (called co-product) and in this case the allocation of all inputs and emissions has to be done (predominantly on the economic basis of co-products) based on the total sum of 100%. The unit process has to maintain a balance between all input materials, product output and emissions.

For this project, the goal was to obtain data for unit processes which represent significant operations in a forest, mill or plant so that users of the data can understand and/or relate to the various components of a product system and also so that critical reviewers can conduct technical analyses. This lowest level processes include all the common processes, materials, energy sources, transport, wastes treatment which are necessary to build the next level of data, single forestry and wood products unit processes, for which data was collected.

Process trees are typically built up in a "bottom up" fashion. This means typically starting with processes such as resource extraction, and ending with a complete description of a product. Often the processes needed are already available in a library. In that case, a link is made between a process record that is in the project and the required one in the library.

Processes include the single unit processes for each of the outputs of the forestry and wood products group – these product processes were divided into sub-processes as required. Each product group included all the identifiable (subject to data being obtainable) single unit processes (e.g. sawing, drying, gluing etc) which are built from different materials, energy sources, transportation, etc (according the processing diagram/ map). The number of unit processes ranged from one to over a dozen for some products.

3.4 Reference unit

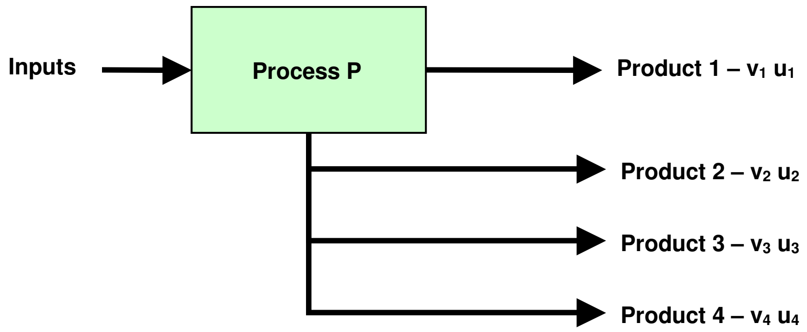
The reference unit (sometimes called functional unit in a full life cycle analysis) is a fixed point at which alternative services can be compared in a Life Cycle Assessment study. In inventory analysis, it provides a reference to which the input and output data are normalised. Also, the reference unit is used to relate intermediate flows between the components of the project; i.e. when the product output of one process acts as the material input to another process, then the flow and corresponding unit of flows must be the same. The reference unit for each of the five production groups is shown in Table 15.

Table 15 Input and output units

Product group	Input units	Output units
Softwood and hardwood logs	na	m^3
Sawmilling of softwood and hardwood	m^3	m^3
Veneer, Plywood and LVL	m^3	m^3-e - Product type (thickness) x m^2
Particleboard and MDF	m^3	Product type (thickness) x m^2
Glulam and Engineered I-beams	m$^{3/}$ m^3-e	m^3-e and Lm

3.5 Allocation

Each unit process is supplied with inputs, and generates output products, by-products and recyclable wastes, as well as pollution which must be carried by the environment (Howard *et al*, 1999), as shown in Figure 10.



Source: Howard *et al*, 1999.

Figure 10 Allocation principles

Allocation rules were used to assign the relative burdens between all the products, whether main product, by-product, recyclables or waste. The ISO 14041/6.5.3 (ISO 14041, 1998) stepwise procedure was followed. Materials and energy flows as well as associated environmental releases were allocated to the different products, according to the following rules:

- Allocation was avoided if possible by dividing the process and using more detailed data or expanding the system so that co-products are included. Thus many of the smaller identifiable individual processes within a mill were aggregated together as a single process. Lack of disaggregated data also influenced these aggregations.
- Within the process boundary, the physical relationships between inputs and outputs were used to reflect the way in which the inputs and outputs are changed by products or functions delivered by the system.
- Outside the process boundary, the product **value** (including product, by-product, recyclables or waste) was used to allocate environmental burdens, i.e. economic allocation was used.

The **economic allocation** principle for each emission j based on the value of each product i produced from a process (Figure 10) over a given time period was the following:

$$p_{ij} = P_j . v_i . u_i / V$$

where

p_{ij} = emission j allocated to product i
P_j = total of emission j produced by the process
v_i = value of product i per unit produced
u_i = number of units of product i produced
$V = \Sigma\, v_i\, u_i$ = total value of products produced by the process.

This economic allocation principle is based on assigning burdens in proportion to the contribution of the product stream to the profits arising from the process. Allocation to wastes was zero as the unit value was zero and conversely the allocation to high value products approached 100% of the emissions from the process.

In the forestry and wood products industry, there are many instances of co-products which are fed back into the processing (e.g. sawdust used as fuel), or which are used by others for related products (e.g. wood chips from thinnings and/or low grade logs).

3.6 Process description and mapping

LCI data for wood products can be represented as: data for material flow in the life cycle process, data for energy and resource consumption, and data for environmental load. The process diagrams provide the detailed road maps for data to be collected and specified the required data sources, types, quality, accuracy, and collection methods before filling in the flow diagram and worksheets with numerical data.

From the visits to forests, mills and plants, comprehensive process maps were drawn up and then related individual processes were aggregated into a small number of processes which became the unit processes required of the LCI. The selection of unit processes was based on clearly defined steps in the process of producing the output products and influenced by the availability of data (or lack of being able to disaggregate available data).

The steps involved are illustrated by the following examples.

3.6.1 Identifying the production system

The forestry product group example (Figure 11) focuses on the growing and harvesting of sawlogs, pulplogs and other products from native forest and softwood plantations. It includes all inputs and emissions associated with collection of seed, production of seedlings, establishment of the forest, application of fertiliser and other chemicals, protection and monitoring of the forest, road construction, and harvesting and transporting of logs to mills for processing. Data are based on values provided by forest owners and managers, individual contractors, published literature and existing LCI models of processes outside the scope of this study (e.g. oil refining or fertiliser production).

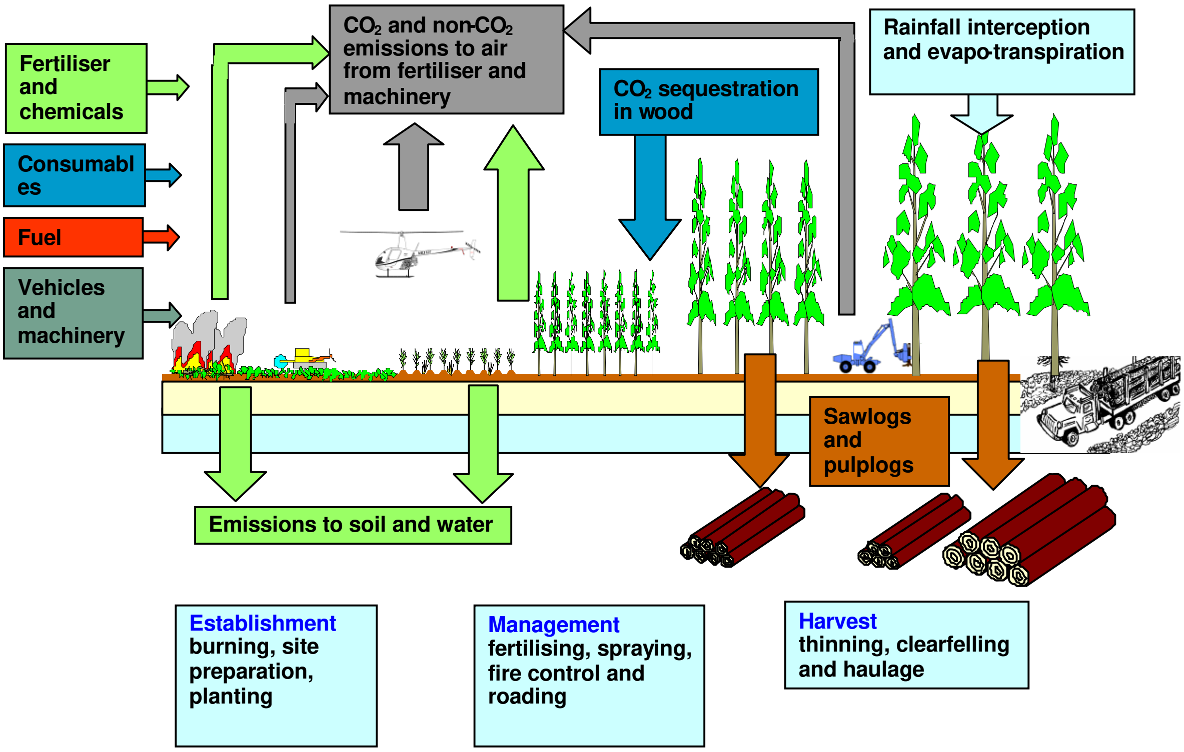


Figure 11 A typical plantation softwood production system

3.6.2 Describing the manufacturing process

This plywood example of a manufacturing process shows the operations for plywood (Figure 12) from veneers (usually an odd number although using an even number of veneers is not uncommon), and depicts the individual production processes including inputs and outputs from the process. The veneers are layered then bonded together with the grain of adjacent sheets at right angles to each other.

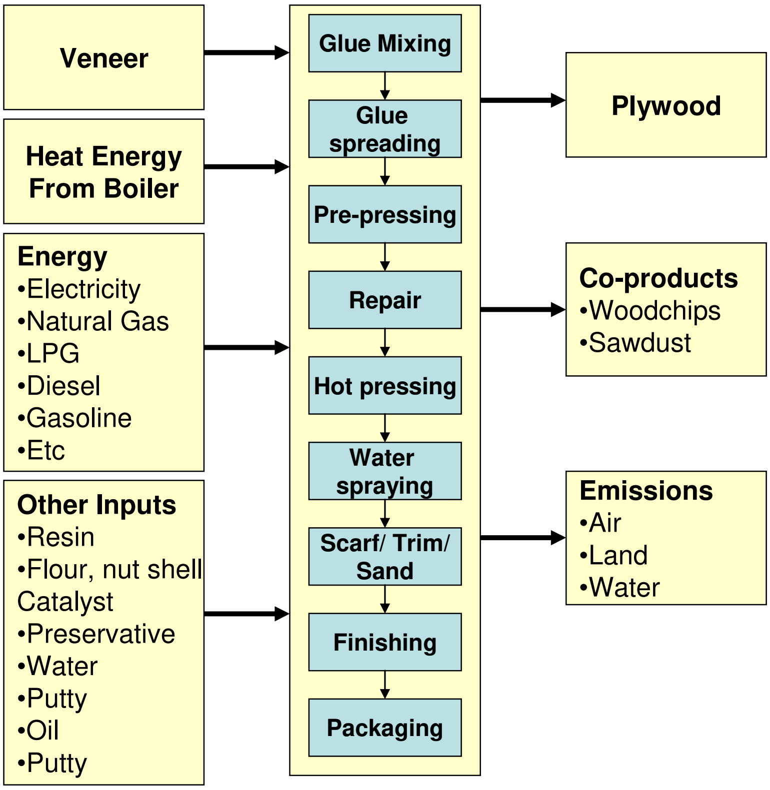


Figure 12 Typical plywood manufacturing process

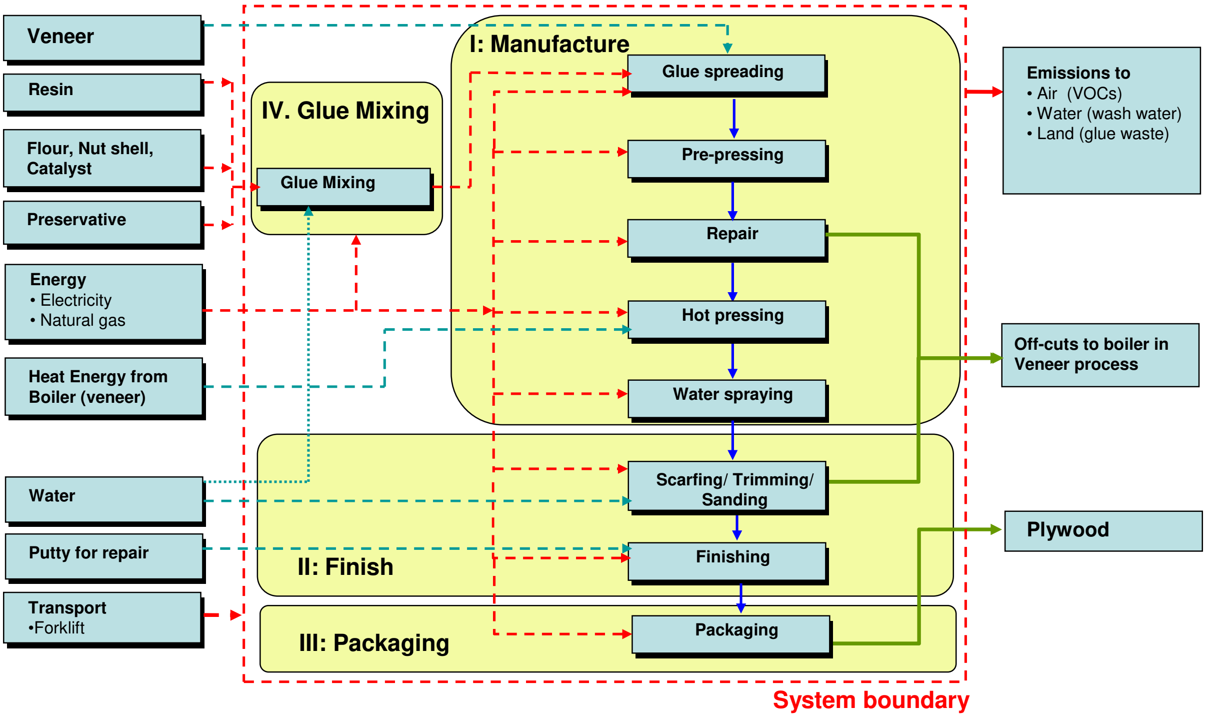


Figure 13 Process map including system boundary for plywood manufacturing

3.6.3 Preparing a process map

From the understanding of the processes involved, a process map is prepared to determine the unit processes to be included in the SimaPro model. The example plywood production unit processes were reduced to just three: *plywood manufacture* (adhesive spreading, pre-pressing, repair, hot pressing, and water spraying), *plywood finish* (scarfing/ trimming/ sanding and finishing) and *plywood packaging* (Figure 13). An additional unit process of *adhesive mixing* was also created.

3.7 Environmental impact modelling

After data verification, the data gathered was compiled to construct a model of all the processes involved using the SimaPro 7.1 process modelling software. SimaPro (Pré Consultants, 2008) is a professional tool to collect, analyse and monitor the environmental performance of products and services. It is a tool with which it is easy to model and analyse complex life cycles in a systematic and transparent way, following the ISO 14040 series recommendations.

SimaPro comes with several inventory databases with thousands of processes, plus the most important impact assessment methods. Pré Consultants is also reseller of the Ecoinvent database (Ecoinvent, 2007), an up-to-date LCI database with 2500+ processes. This database has only limited versions of Australian processes. The most useful part of the Australianised database which is supplied with SimaPro is the sources of energy (e.g. electricity generation – all by State, and other fuels used in Australia). The SimaPro database was also a source of models for the common processes, such as transport modes and imported products such as adhesives, which were modified to suit Australian usage.

SimaPro is thus essentially a modelling tool with which to create the various process models using specifically created models for the processes for which data was collected. The availability of impact measures such as CO_2-e and Eco-indicator 99 minimised the effort in producing results. The role of SimaPro in this project was similar to using a Microsoft Excel spreadsheet to develop models and input your own individual data. A typical SimaPro process map is shown in Figure 14.

Input tables were constructed for each significant step (as a unit process) of the production process. Modelling results were checked and transferred for report compilation and was followed by an audit as well as a sensitivity analysis.

From the visits to forests, mills and plants, comprehensive process maps were drawn up and then related individual processes were aggregated into a small number of processes which became the unit processes required of a LCI. The selection of unit processes was based on clearly defined steps in the process of producing the products and influenced by the availability of data (or lack of being able to disaggregate available data).

These unit processes were modelled as an integrated SimaPro model to calculate the resulting inputs and outputs per functional unit (e.g. cubic metre of log or sawn timber or square metre of a plywood or particleboard) including all raw materials from growing forests and common processes such as Australian energy sources.

All data inputs were gathered, searching for primary data first, then supplemented with secondary data and finally estimates calculated or otherwise determined from other available sources. All of the data was then modelled together across the defined scope and system boundaries (physical and temporal).

The data inputs and outputs per functional unit were averaged for input into models developed in the SimaPro life cycle assessment software (Pré Consultants, 2008) for all products except logs from forests where seven individual models were created.

The result is a LCI of all inputs and outputs for the range of products listed in Table 16.

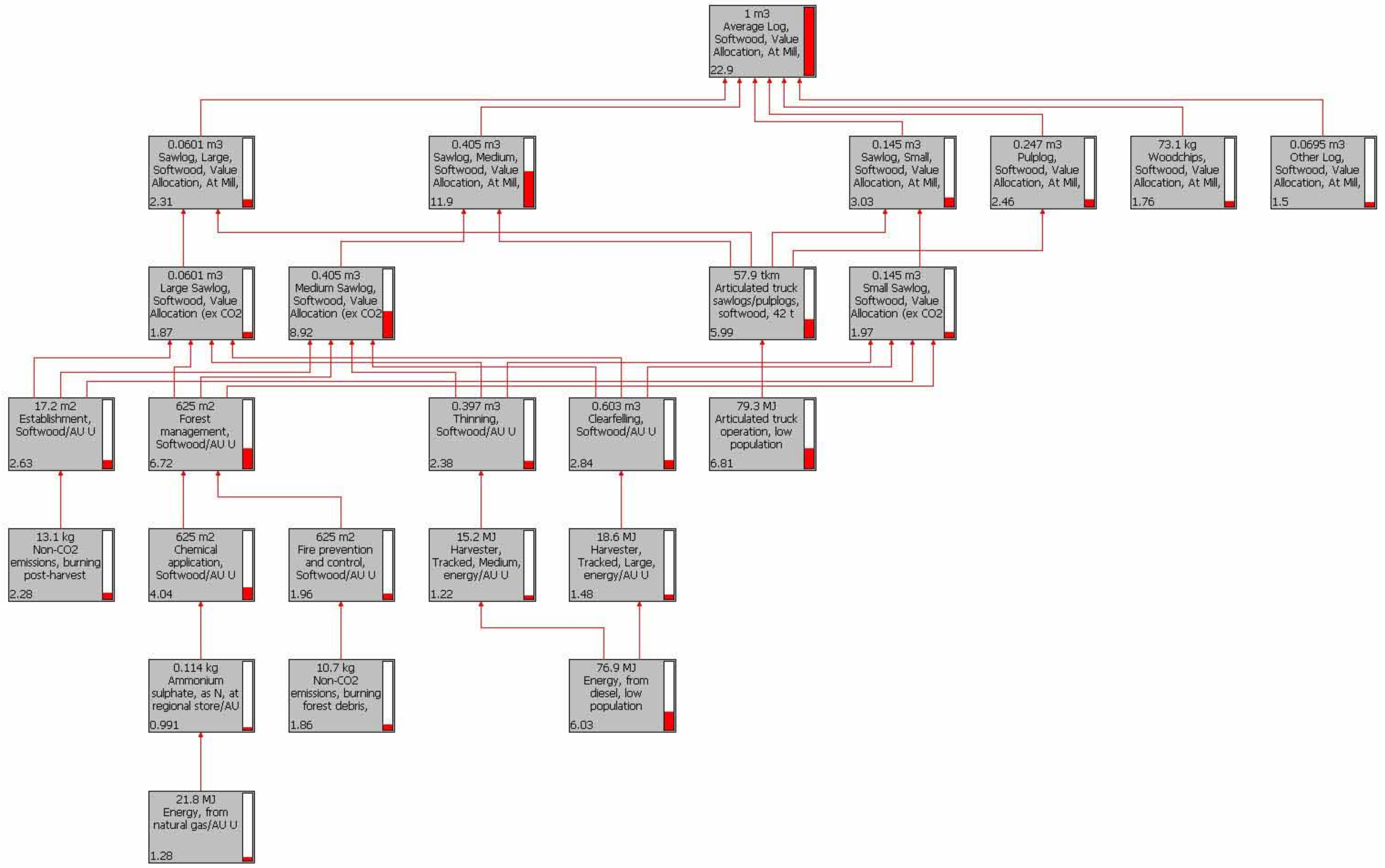


Figure 14 Example of SimaPro output for total CO_2-e emissions associated with producing 1 m^3 of an average softwood log delivered to mill.

Table 16 Forestry and wood products contained in the LCI database

Product	**Reference unit**
Forestry	
Sawlog, Large, Softwood, At Mill	m^3
Sawlog, Medium, Softwood, At Mill	m^3
Sawlog, Small, Softwood, At Mill	m^3
Woodchips, Softwood, At Mill	t
Average log, Softwood, At Mill	m^3
Veneer log, Hardwood, At Mill	m^3
Sawlog, High Quality, Hardwood, At Mill	m^3
Sawlog, Low Quality, Hardwood, At Mill	m^3
Average log, Hardwood, At Mill	m^3
Sawn timber	
Timber, Softwood, Rough sawn green	m^3
Timber, Softwood, Planed green	m^3
Timber, Softwood, Rough sawn kiln dried	m^3
Timber, Softwood, Planed kiln dried	m^3
Timber, Hardwood, Rough sawn green	m^3
Timber, Hardwood, Planed green	m^3
Timber, Hardwood, Rough sawn kiln dried	m^3
Timber, Hardwood, Planed kiln dried	m^3
Plywood and LVL	
Plywood, Interior, 9mm	m^2
Plywood, Interior, 12.5mm	m^2
Plywood, Exterior, 6.5mm	m^2
Plywood, Exterior, 12mm	m^2
Plywood, Exterior, 19mm	m^2
Plywood, Formply, 17mm	m^2
Plywood, Formply, 19mm	m^2
Plywood, Structural, 12.5mm	m^2
Plywood, Structural, 18mm	m^2
Plywood, Structural, 19mm	m^2
Plywood, Flooring, T&G 12mm	m^2
Plywood, Flooring, T&G 15mm	m^2
Plywood, Flooring, T&G 17mm	m^2
LVL, 90x36mm	m^2
LVL, 200x45mm	m^2
LVL, 240x63mm	m^2
Particleboard and MDF	
Particleboard, 9mm	m^2
Particleboard, 16mm	m^2
Particleboard, 16mm moisture resistant (MR)	m^2
Particleboard, 25mm moisture resistant (MR)	m^2
Particleboard, 33mm moisture resistant (MR)	m^2
Particleboard, 19mm flooring	m^2
Particleboard, 19mm decorated	m^2
MDF, 12mm	m^2
MDF, 18mm	m^2
MDF, 25mm	m^2
MDF, 12mm decorated	m^2
MDF, 18mm decorated	m^2
MDF, 25mm decorated	m^2
Glulam and Engineered I-beams	
Glulam	m^3
I-beam, 200x70mm OSB web & pine flanges	Lm
I-beam, 280x70mm OSB web & pine flanges	Lm
I-beam, 360x70mm OSB web & pine flanges	Lm
I-beam, 240x63mm ply web and LVL flanges	Lm
I-beam, 300x63mm ply web and LVL flanges	Lm
I-beam, 360x63mm ply web and LVL flanges	Lm

3.8 Common processes

To ensure compatibility between the various gate-to-gate models when integrated into one model to obtain cradle-to-gate results, category of models called *common processes* was established. No process model could use models for such items as energy, transport, imported materials, chemicals etc that were not in the *common processes*. Where required models existed elsewhere, a copy was made and incorporated into the forestry and wood products database.

3.8.1 Energy sources

All the energy sources used were collated from the best Australian models available in the libraries supplied with SimaPro. Only Australian average energy sources were used, i.e. there were no regional differences between energy sources.

3.8.2 Transportation

While models of typical transportation existed in the SimaPro libraries, there were many unique vehicles used in forestry. These specialised vehicles, such as harvesters, were created by modifying the model of a truck or bulldozer nearest to the capabilities of the required equipment. Since the main input was fuel, records of fuel use were used to amend the models.

3.8.3 Imported materials

Models of imported materials were again obtained from the various modelling libraries in SimaPro and modified, if necessary, to include additional transport to Australia.

3.9 Assumptions

3.9.1 General

All assumptions made during this project were recorded in the quality assurance documentation. Wherever information is lacking or from a sensitive source, assumptions have been made based on theoretical approaches supported by CORRIM, other LCI studies, SimaPro data, Boustead Data, industry norms, etc. General assumptions include:

- Products selected are typical products based on data provided by manufacturers, with some minor products included for completeness and to ensure input materials were available for other product groups.
- All data on process and materials input from plant personnel and manufacturers was accepted as accurate.
- The input data for the LCI modelling are based on weighted-average data from a range of forests, mills and plants producing forestry and wood products.
- Energy used is reported by energy source (e.g. coal, diesel fuel and electricity) and the upstream modelling assumed Australian average energy production for all energy sources, i.e. there were no local energy sources included in the LCI modelling.
- Road transportation is assumed in all cases, which is conservative from an energy consumption and emissions standpoint (i.e. higher energy and emissions than rail).
- LCI input and output materials and processes which are not part of the forestry and wood based product growing or manufacturing (e.g. adhesives, energy, transport, etc) were collected and documented as common processes based on available Australian data.
- All allocation of resource usage and emissions were on an economic value of products and co-products.
- Emissions are taken from NPI (National Pollutant Inventory) reports and greenhouse gas reports, as well as measurements for other purposes to ensure the best possible data quality.

- Moisture content of wood was as follows: green chip was considered to have a wet-basis moisture content of 50%; sapwood was considered on an oven-dry basis at 60%; log cores (heartwood) was considered on an oven-dry basis at 25%; and bark and wood waste was considered on an oven-dry basis at 7%.
- Unaccounted for mass was treated by a mass allocation rule and assumed to be due to moisture loss during processing.
- Although basic density of wood varies with tree age and location up the stem (e.g. butt verses top logs), the density was assumed to be the same average for different products due to lack of available data. Average density of different products was based on reported densities for different species from Ilic *et al* (2000) and the weighted average mix of species mix comprising each product.

3.9.2 Forest steady state

A key assumption was that the forest system was in a steady state both with respect to carbon in pools of debris and to management operations (i.e. there is no change in land use or management systems over time). This avoided complications caused due to changes in soil carbon associated with conversion of previously unharvested forest or agricultural land to plantation or forest managed for wood production. It also allowed a direct approach for data collection where current inputs of materials, energy and natural resources were assumed to relate to current wood production outputs. This contrasts with the approach used in CORRIM, where the varying intensities of management activities were assumed to relate to a predicted rate of future wood production.

To meet the steady state assumption for softwood plantations, all newly planted land, not previously managed for wood production and all activities relating to the establishment operations on this land were excluded from the system boundary. In the native hardwood forestry case studies, wood production from old growth forest was excluded except for the Tasmanian study where some old growth logging still takes place. In this study, only forest operations in regrowth forests were covered. Thus, it was assumed that all wood harvested from native forests in the regions surveyed was from regrowth forests.

3.9.3 CO_2 emissions from burning and decomposition in forests

With the steady state assumption, it follows that CO_2 sequestration and emissions are balanced over a forest rotation. This approach is consistent with existing data that indicates that there is little change in soil carbon in forests that are at steady state. Thus, for this project, a conservative approach was been taken regarding soil carbon whereby any inputs from litterfall and root turnover were assumed to be converted back to CO_2 (i.e. have no effect on net CO_2 emissions). Further, CO_2 emissions from fuel reduction burns and post-harvest burning of slash and wildfire were ignored. Emissions from combustion of fossil fuels associated with fire suppression efforts (e.g. tankers, aircraft, etc.) were included.

3.9.4 Non-CO_2 greenhouse gas emissions in forests

Major non-CO_2 GHG emissions from native forests and plantations include those arising from burning of slash and forest debris, application of fertiliser as well as combustion of fossil fuel. Non-CO_2 GHG emissions from the burning were estimated from the estimated amount of material burnt and emission factors published by the IPCC (IPCC, 2006). Emissions of N_2O from fertiliser were estimated from rates of N_2O production per unit N fertiliser applied (1%, IPCC, 2006). Non-CO_2 GHG emissions from normal decomposition, growth and wildfires were assumed to be zero as these were assumed to occur independently of wood production.

3.9.5 Forest residues burnt in post-harvest burns

Data on forest residues from harvesting is currently not routinely collected for either native forests or plantations. Where possible, the mass of harvest residues and proportion burnt were based on estimates from forest managers. Otherwise the mass of harvest residues burnt was based on reported residue factors for different forest types and harvest regimes, and proportions burnt reported by Raison and Squire (2007), the total volume of wood harvested from forest managers and wood densities based on Ilic *et al* (2000).

3.9.6 Water use in forests

Total water use by both softwood plantations and hardwood native forests was estimated from a relationship between total rainfall and evapo-tanspiration for forests developed by Zhang (2001) and allocated to harvested wood products. These estimates were compared with actual measurements of rainfall and catchment water yield for forested catchments (Benyon *et al*, 2006; Bubb and Croton, 2002; Brown *et al*, 2005; Cornish and Vertessy, 2001, Vertessy *et al*., 2001).

Because, even for bare soil, some moisture is lost through evaporation, water-use for wood production from plantations was expressed relative to water-use by a base-case land use (pasture). This base-case water use was estimated using the Zhang relationship for pasture and average rainfall figures for the forest region from the Bureau of Meteorology. In contrast, water-use for native forests available for wood production was expressed relative to that for forests reserved for conservation purposes using results from previous studies showing the change in evapo-transpiration and water yields for stands of different ages. These data indicated that average evapo-transpiration for a forest harvested once every 60-120 years was likely to be 10-20% greater than that for a stand burnt and regenerated once every 240 years (the nominal frequency of wildfire in ash-type forests prior to European settlement (Moran and O'Shaughnessy 1974, Vertessy *et al.* 2001). Thus, the additional water use by stand harvested for wood production was assumed to be 15% of that for a stand reserved for conservation purposes (or 13% of the total water use by the harvested stand estimated from the Zhang relationship).

3.9.7 Emissions from herbicides, pesticides and fertiliser

The plantation forestry case studies included amounts of herbicides, pesticides and fertilisers applied in both nurseries and across the forest estate. As a result of the stringent controls placed on pesticide and herbicide use in forestry operations, emissions to air and water were assumed to be minimal (Jenkin and Tompkins, 2006). Leaching losses of nitrate, ammonium, phosphate, potassium and sulphate from fertiliser were estimated from a range of published studies (Frank and Stuanes, 2003; Harriman, 1978; Hunter and Hunter, 1991; Khanna *et al*, 1992; Lee and Jose, 2005; and Raison *et al*, 1992).

- N as NO_3^- : 13% (+/1 5%) of applied N,
- N as NH_4^+: 2% (+/- 2%) of applied N,
- P as PO_4^{3-}: 1% (+/- 1%) of applied P,
- K as K^+: 30% (+/- 5%) of applied K, and
- S as SO_4^{2-} 40% (+/- 10%) of applied S.

Emissions from fertiliser to air covered in this study included N_2O and NH_3. N_2O emissions were assumed to comprise 1% of applied N fertiliser (IPCC, 2006), while NH_3 emissions were assumed to comprise 30% of the applied urea N (May and Carlyle, 2005).

3.9.8 CO_2 sequestration in wood

Total CO_2 sequestration, in this study was defined as the CO_2 sequestered by the tree to produce the biomass removed as logs and woodchips from the forest. This was estimated from average basic densities (sourced from Ilic *et al*, 2000) for the species (or species mix) relevant to each case study with an assumed carbon content of 50%. Net CO_2-e sequestration was defined as the total CO_2 sequestration minus the total GHG emissions either directly or indirectly associated with forest management, harvesting and haulage.

3.10 Data quality

The project followed the data quality requirements specified in ISO 14044:4.2.3.6, which can be broadly categorised into:

- *Representativeness* - a qualitative and quantitative assessment (where appropriate) of the degree to which the data reflects the true population of interest shall be provided for the study, including geographical coverage, time-related coverage, technology coverage, and market share;
- *Consistency and reproducibility* - ensured by adequately documenting the application of study requirements and Life Cycle Assessment methodology, and data collection, analysis and validation methods used, and;
- *Quality of data* - assumptions and limitations and critical review.

3.10.1 Data integrity

It was crucial that the level of confidence in LCI data be appropriate for the decision to be made. The ISO 14041 (ISO 14041, 1998) clause 5.3.6 provides standards for data quality requirements and ISO 14041, clause 6.4.2, gives data validation procedures. The standard contains a definition of data quality as the "characteristic of data that bears on their ability to satisfy stated requirements". Furthermore it is stated that "Data quality should be characterized by both quantitative and qualitative aspects as well as by the methods used to collect and integrate those data".

Generally, mass balance was performed on primary and operating inputs and corresponding outputs, though it can be extended to other categories. Mass balance calculation is a way to ensure the inputs and outputs are properly accounted for.

Energy balance was done for electricity consumption, although it can be extended to the use of other fuels, such as in operating a chain saw. Once data is collected and analysed for the unit process, the LCI of the process chain can be determined.

Wood fuel followed through the LCI processes was on a mass basis and then converted to an energy value at the end. This eliminates any errors that could occur with differences in moisture content, energy content values used, and efficiencies between the different processes. Wood moisture content was expressed on an oven-dry basis. Actual wood densities were used.

3.10.2 Data aggregation

LCI data of processes was aggregated as a process average. These were computed for the same physical process for averaging the differences in performance (and hence data) for different time or product volume variations. Process averaging, usually, must take place over a reasonably homogeneous population. For example, those under approximately the same production conditions, technology, input emission characteristics and scale.

Each input and emission from a production process was an average from available similar processes and only the average was input to the process model in SimaPro. The LCI data was separately aggregated without infrastructure contribution. Data aggregation at unit process level applied a weighted average, where the weights were computed on the share of total production of the all the sites for which data was collected.

3.10.3 Data validation

A check on data validity was conducted during the process of data collection to confirm and provide evidence that the data quality requirements for the intended application have been fulfilled. Validation involved establishing, for example, mass balances, energy balances and/or comparative analyses of release factors. Other validation measures such as comparing collected or estimated data with published data were undertaken, as required.

Final calculation of inventory was in identifying and compiling the elementary flows associated with the inputs and outputs. Life Cycle Assessment software would normally contain substance emissions in its database for the input of energy and materials, and where accounting for fugitive emissions is appropriate references (Department of Environment and

Heritage, 2006a and Department of Environment and Heritage, 2006b) were used. However, the production and mix of input materials had to be correctly specified. For example, in using electricity, its source of supply (such as from coal or hydro) or the grid-mix in case of a common supply had to be established. For output emissions, such as burning fuels, there were ready reference sources on which to model or cross check common processes.

Treatment of missing data followed the ISO14044:4.2.3.6.3 (ISO 14044, 2006) practice as follows: the treatment of missing data was documented and, for each unit process and for each reporting location where missing data are identified, the treatment of the missing data and data gaps resulted in "non-zero" data values that is explained, a "zero" data value if explained, or a calculated value based on the reported values from unit processes employing similar technology.

Sensitivity analysis was a useful tool during development of the LCI database to determine whether results were sensitive to missing, excluded or uncertain data, based on tests with proxy data; and analysis of the effect of different methods for co-product allocation, or for comparison of specific situations to industry averages.

3.10.4 Data uncertainty

A pedigree matrix with a series of indicators provided a scoring system to communicate the quality of the data for each unit process, as shown in Table 17, and was recorded in the Quality Assurance documentation.

Table 17 Quality Assurance pedigree matrix

Indicator Score	**1**	**2**	**3**	**4**	**5**
Reliability	Verified data based of measurements [b)]	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data from a smaller number of sites or shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than six years difference	Less than ten years difference	Less than fifteen years difference	Age of data unknown or more than fifteen years of difference
Geographical correlation	Data from area under study	Average data from larger area in which area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but the same technology	Data on related processes or materials but the different technology

Data uncertainty was determined as follows:

- Data was obtained from measurement, estimation, calculation or secondary sources, and the likely distribution type and its parameters selected from the available list in SimaPro (uniform or triangular distributions may be appropriate); or
- The uncertainty present was estimated by making subjective estimates of the sources of variance using a structured, reproducible approach of the pedigree matrix available in SimaPro.

3.11 Quality Assurance and documentation

A significant task for the project participants was the documentation of data collected and situations under which they were collected (called meta-data or administrative data) because the recording of this information had a fundamental role in the development of data for the LCI database. When this information is available, the value of the collected data is increased and a later user can form a personal opinion of the quality, usefulness and representativeness of the data. For instance, instead of providing a single value for data, inclusion of the number of sources from which data is collected (e.g. six factories), the number and method of the measurements taken (e.g. 3 trials of sampling), the time period of the study (e.g. 2005), the process technology, competency of the practitioner and others will facilitate the exchange, storage and retrieval of Life Cycle Assessment-data without loss of transparency.

Typical documentation of data collection systems included: objectives of the data collection system, and underlying technical and scientific understanding, data requirements with estimates of importance and quality needs, comparison to existing databases of similar product systems, treatment of data gaps, and methods of data collection including potential sources, locations and frequency.

ISO/TS14048 Life cycle assessment - Data documentation format (ISO 14048, 2002) was applied for each unit process. As a minimum, documentation included the following was recorded in a standard format in a spreadsheet designed for the purpose:

- Process name that unambiguously describes the process features,
- Quantitative reference (functional unit or reference flow) that the input and output data refer to,
- Valid time span to which the model of the process applies, and unless projections or other forecasts have been applied, the valid time span is identical to the time of the primary data collection,
- Valid geography describing the geographical area or location for which the process and data is valid, and is identical to the area or location of the data collection, unless extrapolations from other areas have been performed,
- Technical scope of the process (in terms of specified operations or transformations included in the data, or simply as "from ... to ..." stating the first and the last operation of a chain, e.g. in a transport route, on a site, or in a production line),
- Detailed technical content and functionality of the process, and
- Data acquisition (data collection and treatment) procedures at the process level.

A Quality Assurance procedure was in place to ensure that the documentation procedures were carried out and could lead to peer review. The recorded information was made available to independent reviewers to check that the information on the LCI development process was adequately recorded. The three sections were:

- *Administrative*: general and administrative information about the study.
- *Product system*: information about the studied system including definition of function and functional unit, system boundary, representativeness of dataset, aggregation method used and others.

- *Unit process*: information including data collection, process input-output, treatment of missing data, data quality (pedigree matrix) and so on.

The information was tabled in an Excel spreadsheet which contained the Quality Assurance reporting fields and other information such as Pedigree Matrix which describes the quality of the data and provides an indirect quantitative estimate of the accuracy of the LCI data for each and every product.

3.12 Peer review

Reviewing LCIs was an integral activity in collecting LCI data. There are two types of review, data and procedure. The data review was essential to reduce errors and uncertainty in data. The data review was undertaken by those experienced in Life Cycle Assessment and knowledgeable in the processes under review and included adequacy of data, factual validation of data and checks on calculations. The data review ensured that data and calculation procedures used were adequate, scientifically and technically valid, adequately documented and justified when necessary. The procedural or compliance review was an assessment of how well the process of data collection and documentation has been carried out.

The Quality Assurance checklist was the basis for checking by the two international and independent experienced LCI reviewers. The first Dr Kwangho Park (Director YES (Your Environment and Sustainability) Consulting Co. Ltd, Korea - key developer for Korean National LCI database for building Materials), provided feedback on the adequacy of the LCI data for use in an LCI database during its development and provided guidance on ensuring that the recorded data satisfied ISO standards, the second Dr Maureen Puettmann (CORRIM representative and WoodLife LCA Consulting, Corvallis, Oregon, USA - a key researcher in the CORRIM studies), checked the final reports and provided feedback on the completeness and compliance of the LCI process as recorded in the reports. The Quality Assurance checklist thus contains reviewer's judgment of the quality of the LCI study at two different levels.

The critical review process considered the following aspects of the study (adopted from ISO 14044:2006(E), Section 6):

- methods used to carry out the LCI are consistent with the International Standards,
- scope of the study, including system boundary definition, functional unit, allocation rules are justifiable given the goal of the study,
- methods used to carry out the LCI are scientifically and technically valid,
- data used are appropriate and reasonable in relation to the goal of the study, and
- study report is transparent and consistent.

ISO14044:5 (ISO 14044, 2006) is clear on the general reporting requirements. In essence, the LCI study reports completely and accurately without bias to the intended audience. The results, data, methods, assumptions and limitations are transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCI study. The report also allows the results and interpretation to be used in a manner consistent with the goals of the study.

3.13 Life Cycle Inventory for forestry and wood products

The final step was the creation of a LCI database of Australian forestry and wood products covering the following categories of forestry and wood products;

- Softwood plantation and native hardwood forests;
- Softwood framing and hardwood timbers;
- Veneer and plywood, and LVL;
- Particleboard and MDF; and
- Glulam and engineered I-beams.

Users of such a database cannot access the process models or view any detail of the components or processes which contribute to the production of the product. It is essentially the end point of a comprehensive collection of processes and data, which when modelled in SimaPro provide the outputs for users of a LCI database.

The data made available in this report is therefore a weighted average by value of the wood products in Australia and no producer can be identified from these results. The LCI is a list containing the quantities of emissions released to the environment and the amount of energy and materials consumed. This information can be organized by life cycle stage, by media (air, water, land), and by specific process.

Product level LCI information is as listed in Table 18 from the Quality Assurance spreadsheets for each product in the forestry and wood products LCI project.

Table 18 Product level LCI information

Product information	Product description: Descriptive and unambiguous name of product including description of distinctive properties, such as moisture content, size etc.
	Quantitative reference including functional unit (units, amounts etc.)
	Technical scope describing the system boundary
	Aggregation type and methods used for data
	Technology description and graphical representation of system and unit processes
	Representativeness of data including geographical, technology and market coverage
	Data acquisition methods used and % of production covered by the study
Modelling & validation	Intended application
	Information sources used including types
	Modelling choices and description of major exclusions
	Allocation description on the types of allocation used for co-products and prices, where economic allocation was used.
	Data quality statement by the data generator about the coverage
	Validation information as to how data was validated
	Other information to provide advice to users
Aggregated input-output table	Data in this category is aggregated over all unit processes as representing the final input-output flows of the system. This data is derived from input-output data for unit processes.
	Typical information relating to input materials, energy, chemicals and others including their values, and the sources of their flows, i.e. elementary, technosphere and description on how these values were obtained and references used.
	Typical information on outputs will be similar to that of inputs with additional description of environmental compartments into which waste and emission flow.
Aggregated elementary flows	Data in this category is aggregated elementary flows resulting from material flows in Aggregated input-output table. These flows are defined by units, amount and CAS (Chemical Abstract Service, www.cas.org) number where available.

4 RESULTS

4.1 Forestry

4.1.1 Land

Land use per unit wood production for softwood plantations, as estimated from the total plantation area and the total annual volume harvested averaged 0.06 ha m^{-3} (Table 19). This equated to average rates of wood production of 17 m^3 ha^{-1} y^{-1}. In comparison, land use per unit wood production for native hardwood forests averaged 0.3 ha m^{-3} (3.5 m^3 ha^{-1} y^{-1} (Table 20). The lower land-use efficiency, in terms of wood production, for native forests is a result of lower management intensity (e.g. longer rotation lengths, no fertiliser or pesticide use) and is due to the multiple benefits for which native forests are also managed (e.g. biodiversity, water supply and recreation).

Table 19 Summary of inputs of natural resources, energy and materials for softwood plantation case studies

Item	Unit[§]	Average	Std. Dev.
Natural Resources			
Land	ha/m^3	0.06	0.02
	m^3/ha	17	4
Water	ML/m^3	0.12	0.07
	ML/ha	1.7	0.7
CO_2 sequestration	kg/m^3	830	54
	t/ha	14	3
Forest residues burnt			
Harvest slash	kg/m^3	13	18
Fuel reduction	kg/m^3	12	30
Energy			
Fuel Volume	L/m^3	4.7	1.2
Energy	MJ/m^3	182	46
Materials			
Lubricant	L/m^3	0.08	0.02
Tyres	kg/m^3	0.06	0.03
Steel Tracks	kg/m^3	0.06	0.00
Chains and blades	kg/m^3	0.02	0.00
Gravel	kg/m^3	470	240
Bitumen	kg/m^3	0.1	0.2
Fertiliser (macro elements only)			
N	kg/m^3	0.30	0.27
P	kg/m^3	0.20	0.16
K	kg/m^3	0.06	0.05
S	kg/m^3	0.24	0.22
Herbicide (by active ingredient)			
Atrazine	g/m^3	6.0	4.2
Glyphosate	g/m^3	3.8	4.7
Simazine	g/m^3	3.1	9.6
Hexazinone	g/m^3	2.3	1.5
Triclopyr	g/m^3	0.2	0.7
Other	g/m^3	0.4	0.5
Fungicide (by active ingredient)	g/m^3	0.03	0.03

[§] All units are expressed in terms of total wood volume harvested except water and CO_2 sequestration which are also expressed per unit total harvestable area. Averages are weighted by proportion of total Australian production represented by each case study.

Table 20 Summary of inputs of natural resources, energy and materials for the native hardwood forest case studies

Item	Unit§	Average	Std. Dev.
Natural Resources			
Land	ha/m^3	0.27	0.48
	m^3/ha	3.7	4.0
Water	ML/m^3	0.35	0.6
	ML/ha	1.3	0.1
CO$_2$ sequestration	kg/m^3	1,030	186
	t/ha	3.8	3.6
Management burning			
Post-harvest slash	kg/m^3	168	54
Fuel reduction	kg/m^3	14	26
Energy			
Fuel Volume	L/m^3	9.2	1.3
Energy	MJ/m^3	354	52
Electricity	KWh/m^3	0.05	0.04
Energy	MJ/m^3	0.17	0.13
Gas	MJ/m^3	0.06	0.04
Materials			
Lubricant	L/m^3	0.13	0.06
Tyres	kg/m^3	0.07	0.07
Steel Tracks	kg/m^3	0.10	0.09
Gravel	kg/m^3	260	220

§ Inputs are expressed in terms of total wood volume harvested except for water and CO$_2$ sequestration which are also expressed per unit total harvestable area. Averages are weighted by proportion of total Australian production represented by each case study.

4.1.2 Water

Estimated water use of forest relative to pasture in the same region indicates that softwood plantations use an additional 131-296 mm per year water compared with pasture, while native forests available for wood production use 123-137 mm per year more water compared with those reserved for conservation. Thus, in terms of the effects of forestry on water availability compared with one alternative land-use, the amount of additional water used for wood production averaged 0.12 ML m^{-3} for softwood plantations (Table 19) and 0.35 ML m^{-3} for native forests (Table 20).

These figures should be taken as indicative only, especially for native forests, as they are based on broad assumptions. While the figures for water-use by plantations are within the range reported by others, long-term studies of water-use by native forests are rare and the estimates are based on only three studies of water-use by stands of different ages in the Victorian Central Highlands and NE NSW. In particular, the estimates assume that the frequency of fire in stands reserved for conservation purposes will be 240 years, although current indications are that this is likely to decrease as a result of climate change and other human related impacts.

4.1.3 Fuel and energy

Almost all direct energy use was a result of fuel combustion in vehicles and machinery. Total fuel use in management, harvest and haulage was 4.8 L m^{-3} (183 MJ m^{-3}) for softwood plantations and 9.3 L m^{-3} or 356 MJ m^{-3} for native hardwood forest. This difference was largely a result of less fuel usage during harvest (1.9 *vs.* 4.5 L m^{-3}) and, to a lesser extent, haulage (2.3 L m^{-3} *vs.* 3.8 L m^{-3}) in softwood plantations. This was due to shorter haulage distances, flatter terrain for harvesting machinery to operate on and greater harvestable volume per hectare in plantations compared with native hardwood forests.

4.1.4 Chemicals

In softwood plantations a range of pesticides and fertiliser are applied either pre-or post planting or, for fertilisers only, near canopy closure or after thinning. The most commonly used herbicides included: atrazine (6.0 g m^{-3}), glyphosate (3.8 g m^{-3}), simazine (3.1 g m^{-3})

and hexazinone (2.3 g m^{-3}) (Table 19). Major fertilisers included triple superphosphate, ammonium sulphate, urea and potassium sulphate, with amounts applied equivalent to 0.30 kg N m^{-3}, 0.20 kg P m^{-3}, 0.06 kg K m^{-3} and 0.24 kg S m^{-3} (Table 19). There was no use of herbicides or fertilisers in native hardwood forests.

4.1.5 CO_2 sequestration

Net CO_2 sequestration in this study is defined as the CO_2 sequestered by the tree to produce the biomass removed as wood products from the forest. Estimated CO_2 sequestered in softwood products ranged 810 to 860 kg m^{-3}, depending on the average density for different species, and averaged 830 kg m^{-3} (Table 19). For products from native hardwood forests, the amount of sequestered CO_2 ranged from 1000 to 1300 kg CO_2 m^{-3} and averaged 1030 kg CO_2 m^{-3} (Table 20).

4.1.6 Direct CO_2 and non-CO_2 emissions

Direct CO_2-e emissions reported here include the emissions of CO_2 from machines and vehicles involved in forestry operations and haulage and the emissions of non-CO_2 greenhouse gases such as N_2O and CH_4 from burning and fertiliser. Total direct CO_2-e emissions from softwood plantations averaged 19 kg m^{-3} compared with 57 kg m^{-3} for native hardwood forests (Table 21).

For softwood plantations, the largest contributors to emissions were haulage (34%), harvesting (27%), and slash and fuel reduction burning (24%). For native hardwood forests, burning (56%) was the largest contributor to total CO_2-e emissions, followed by harvesting (21%) and haulage (18%). Emissions of CO_2 per unit average wood production for native hardwood forests were triple those for softwood plantations. This difference was mainly due to differences in emissions from burning and harvesting (see Tables 19 and 20). Emissions from burning were seven times greater in native hardwood forests, while emissions from harvesting were more than double in native forests compared with softwood plantations.

4.1.7 Direct plus indirect emissions

Indirect emissions include those from upstream processes used to obtain and process raw materials, produce and distribute fuel and energy, and manufacture machines and infrastructure. Indirect emissions comprised 27% of total emissions for 1 m^3 of an average softwood plantation log, and 13% of total emissions for 1 m^3 of an average native hardwood forest log. The main reason for this difference was additional indirect emissions associated with the production of fertiliser used in softwood plantations (2.4 kg CO_2-e m^{-3}).

Total direct plus indirect GHG emissions arising from growing, harvesting and hauling were estimated to be 26 kg CO_2-e for an average softwood plantation log compared with 65 kg CO_2-e for an average native hardwood forest log (Table 22). Major contributions to total emissions from production of softwood logs included haulage (35%), harvesting and chipping (26%), fertiliser use (16%) and burning (17%, Figure 15a). In native forests the primary factors included burning (49%), haulage (24%) and harvesting (22%, Figure 15b).

In terms of allocation to individual softwood products, total emissions varied from 11 kg CO_2-e m^{-3} for pulplogs to 41 kg CO_2-e m^{-3} for large sawlogs (Table 22). These represented between 1 and 5% of the total CO_2 sequestered in the logs. For hardwood products, there was wider variation in allocation of CO_2-e emissions as a result of the greater variation in product value. Emissions varied from 47 kg CO_2-e m^{-3} for pulplogs or 5% of the total CO_2-e sequestered to 348 kg CO_2-e m^{-3} for 'other logs' or 27% of the total CO_2-e sequestered (Table 22). Thus, for both softwood and all but the highest value hardwood logs, total emissions of CO_2-e and other GHGs arising either directly or indirectly from production, harvest and transport of those logs represented only a small fraction (<12% for hardwood and <6% for softwood) of the amount of CO_2 sequestered and stored as carbon in the same logs.

Table 21 Average direct fuel, energy use and emissions from forestry operations in softwood plantations and native hardwood forests

Process	**Energy Use (MJ m^{-3})**				**Fuel Use (L m^{-3})**				**GHG Emissions (kg CO$_2$-e m^{-3})**			
	Softwood Plantation		**Native Hardwood Forest**		**Softwood Plantation**		**Native Hardwood Forest**		**Softwood Plantation**		**Native Hardwood Forest**	
	Average[§]	S.D.[†]	Average[§]	S.D.[†]	Average[§]	S.D.[†]	Average[§]	S.D.[†]	Average[§]	S.D.[†]	Average[§]	S.D.[†]
Establishment												
Seed/Seedling production	0.4	0.1	0.8	0.7	0.01	0.00	0.01	0.01	0.0	0.0	0.0	0.0
Site preparation	7.3	2.4	3.0	2.1	0.19	0.06	0.08	0.05	0.5	0.2	0.2	0.1
Total	7.7	2.5	3.8	2.8	0.20	0.06	0.09	0.00	0.5	0.2	0.2	0.2
Burning												
Slash burning	na	na	na	na	na	na	na	na	2.3	3.2	29.4	9.4
Fuel reduction burning	na	na	na	na	na	na	na	na	2.1	5.2	2.5	4.5
Total	na	na	na	na	na	na	na	na	4.4	4.7	31.9	5.0
Management												
Chemical application	1.5	1.4	na	na	0.04	0.04	na	na	0.1	0.1	na	na
Emissions from fertiliser	na	na	na	na	na	na	na	na	1.5	1.3	na	na
Fire prevention	2.2	0.7	3.2	8.5	0.06	0.02	0.13	0.20	0.2	0.0	0.4	0.5
Roading	6.4	3.9	26.7	7.2	0.17	0.10	0.69	0.19	0.4	0.3	1.8	0.5
Other	2.0	1.9	1.0	4.3	0.05	0.05	0.03	0.11	0.1	0.1	0.1	0.3
Total	12.1	4.5	31.0	19.9	0.32	0.12	0.85	0.50	2.3	1.1	2.3	1.3
Harvest												
Thinning	29.1	10.7	na	na	0.8	0.3	na	na	2.0	0.7	na	na
Clearfelling	35.9	12.2	173.7	43.2	0.9	0.3	4.5	1.1	2.5	0.8	12.0	3.0
Chipping	8.1	8.1	na	na	0.2	0.2	na	na	0.6	0.6	na	na
Total	73.1	16.9	173.7	43.2	1.9	0.4	4.5	1.1	5.0	1.2	12.0	3.0
Haulage												
Total	90.5	40.8	147.9	40.8	2.3	1.1	3.8	1.1	6.2	2.8	10.2	2.8
Total	183	46	356	50	4.8	1.2	9.3	1.3	18.6	6.7	56.6	2.5

[§] Results are expressed in terms of an average log produced.

[†] S.D. is standard deviation of mean.

Table 22 Average CO_2-e emissions and amount of CO_2-e sequestered in different products from softwood plantations and native hardwood forests, together with the net differences

Forest type	Product	CO_2-e	CO_2-e Sequestered		
		Emissions (kg m^{-3})	Total (kg m^{-3})	Net (kg m^{-3})	Proportion of emissions (%)
Softwood Plantation					
	Sawlog, large	41	810	769	5.1
	Sawlog, medium	32	820	788	3.9
	Sawlog, small	23	860	837	2.7
	Pulplog	11	830	819	1.3
	Woodchips	27	810	783	3.3
	Other log	22	820	798	2.6
	Average log	26	**830**	**804**	**3.1**
Native Hardwood Forest					
	Veneer log	191	1230	1039	15.5
	Sawlog, High Quality	125	1050	925	11.9
	Sawlog, Low Quality	52	1130	1078	4.6
	Pulplog	47	1000	953	4.7
	Other log	348	1300	952	26.8
	Average log	65	**1030**	**965**	**6.3**

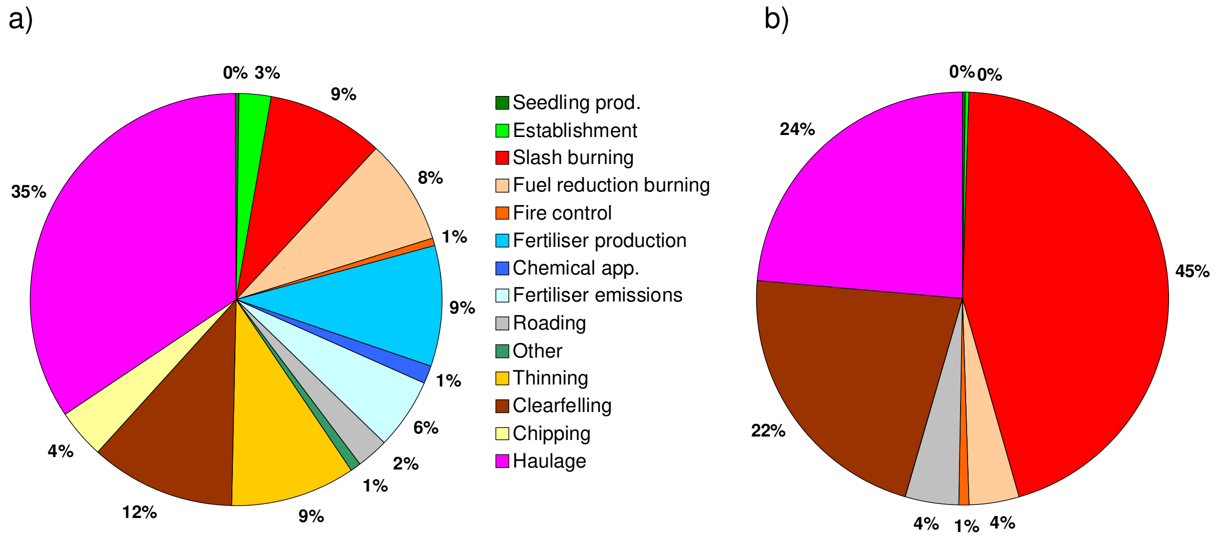


Figure 15 Contributions of different forestry operations to total direct CO_2-e emissions for an average log from a) softwood plantations and b) hardwood native forests.

4.2 Sawmills

All results are presented for 1 m^3 of sawn timber building products before economic allocation is performed. The results focus on the on-site or 'gate-to-gate' results. This allows an easier comparison with other studies and assumes that sawn products are the only products from the mill. Results after economic allocation will be very similar as the allocation procedure attributes most of the results to the sawn products.

4.2.1 Softwood recovery

The recovery of softwood products was approximately 45% from input logs to building products such as structural timber. Approximately 32% was wood chip, 15% was hogfuel shavings and sawdust and the 7% was bark. This means that approximately 2.2 m^3 of log was required to produce 1 m^3 of sawn timber and 0.71 m^3 of wood chips, 0.34 m^3 of hogfuel, shavings and sawdust and 0.16 m^3 of bark. Table 23 compares the recovery rates for softwood sawn products to other softwood sawmill studies.

Table 23 Comparison of softwood sawmill recovery rates

Source	**FWPA LCI Softwood Sawmills**	**CORRIM (Milota 2004)**	**CORRIM (Milota, West and Hartley 2005)**	**EMSOL (2006)**	**Pöyry (1999)**	**Todd *et al* (1998)**	**MBAC (2004)**
Recovery rates green and dry	45%	58%	42%	34%-53%	36%	35%	44%
Chips	32%	26%	27%		35%	33%	33%
Bark	7%	8%	8%			10%	3%

4.2.2 Hardwood recovery

The recovery of hardwood products was approximately 36% from input logs to building products such as floorboards and structural timber. Approximately 21% was wood chip and 43% was hogfuel, shavings, sawdust and bark. This means that approximately 2.8 m^3 of log was required to produce 1 m^3 of sawn timber and 0.6 m^3 of wood chips, 1.2 m^3 of hogfuel, shavings, sawdust and bark. Table 24 compares the recovery rates for hardwood sawn products to other hardwood sawmill studies.

Table 24 Comparison of hardwood sawmill recovery rates

Source	**FWPA LCI Hardwood Sawmills**	**Ximenes & Gardner (2004)**	**Ximines *et al* (2005)**	**Ximines *et al* (2005)**	**Pöyry (1999)**	**MBAC (2004)**	**Todd *et al* (1998)**
Recovery rates green and dry	36%			32% (a)		28%	30%-large 38%-small
Recovery rate for green sawn products		48% (b)	42% (by weight)		45%	38%	
Chips	21%	35%			35%	38%	30% (c)
Bark						3%	
Sawdust and shavings	43%	16% sawdust		20%	11%-sawdust 9%-shavings	31%	

a by weight and based on a recovery to rough green sawn boards of 42% followed by a 76% recovery of the boards to kiln dried and processed DAR boards)

b 33.6% for salvage logs and 52% for quota logs) Also lists 11 studies for commercially grown hardwood with recoveries for green rough sawn boards ranging from 35-55%.

c Large sawmill. Chips were not reported for small mills instead a mixture of shavings and firewood (0.35) and 'mill waste' (0.33) which was noted to be sold

4.2.3 Softwood energy use

A total of 3.08 GJ of thermal energy was required to dry 1 m^3 of softwood (Table 25). Wood residues (hogfuel) were used for 81% of the thermal energy (2.5 GJ) with the remaining 19% supplied by gas (0.58 GJ). This was based on a weighted average of 7 large softwood mills. Only one mill reported not using any hog fuel for thermal energy.

Electricity used on site was 0.23 GJ for the green sawmill (including general site lighting) and 0.13 GJ for kiln fans and heat pumps which gave a total of 0.36 GJ per m^3 of sawn and dried softwood building product. Other energy uses on the site were relatively small – on-site transport for mobile plant was approximately 0.099GJ. Transport of logs to the sawmill was not included as it was considered in the forestry LCI.

Table 25 Breakdown of on-site softwood sawmill energy

Process energy use	**GJ m^{-3} kiln dried sawn product**	**Percentage of total**
Thermal energy for drying - wood residues	2.50	71%
Thermal energy for drying – gas	0.58	16%
Electricity	0.36	10%
Energy for mobile plant	0.099	3%
TOTAL	**3.54**	**100%**

Table 26 compares the energy use to published data for softwoods. Electricity used for FWPA LCI softwoods is higher than CORRIM but within the range of other studies. Most of the energy used in producing sawn timber is consumed in drying (Table 25) and is similar to results from a range of studies, although the source of energy varies. Differences in the total energy used are largely due to the different energy supply systems, for example, the Tasmanian study (Todd *et al* 1998) uses hydro electricity and CORRIM's studies draw upon the US electricity.

Table 26 Comparison of fuel mix and on-site energy use for softwood sawmills

Source	**FWPA LCI Softwood Sawmills**	**CORRIM - West (Milota 2004)**	**CORRIM- South (Milota *et al*, 2005)**	**EMSOL (2006)**	**Todd *et al* (1998)**
Wood (%)	81	58	100	63	100
Gas (%)	19	42		22	
Other (%)				15	
Electricity used at the mill (GJ m^{-3} of product)	0.36	0.21	0.22	0.28	0.48
Heat used at the mill (GJ m^{-3})	3.1	2.9	3.3	3	(2.6)*
Total energy (GJ m^{-3})	3.5	3.1	3.5	3	(3.0)*

* 0.13 m^3 of dry shavings or sawdust and 0.05 m^3 of green shavings or sawdust per m^3 of log input. If the unit is assumed to be per unit of sawn dried timber and a calorific value of 16.2 and 9 GJ m^{-3} is assumed for dry and green wood fuel respectively, then it gives a thermal energy of approximately 2.6 GJ m^{-3} of dried wood.

4.2.4 Hardwood energy use

A total of 2.23 GJ of thermal energy was required to dry 1 m^3 of hardwood (Table 27). Wood residues (hogfuel) were used for 99% of the thermal energy (2.2 GJ) with the remaining 1% supplied by gas (0.025 GJ). This was based on a weighted average of 9 medium to large hardwood mills. There was a diversity of practice including the use of gas and solar kilns. However, large mills that used wood residues dominated the weighted average.

Total electricity used on site was 0.50 GJ per m^3 of hardwood sawn timber product including general site lighting and 0.055 GJ for kiln fans and heat pumps. There was a large range in electricity use reported. The values for total site electricity ranged from 26 to 108kWh/m^3 of log input. However, 5 of the 13 surveys are in the 70-80kWh/m^3 log input range and 4 are in the 40-60kWh/m^3 of log input range. As for softwood, other energy uses on the site were relatively small – on-site transport for mobile plant was approximately 0.099GJ.

Table 27 Breakdown of on-site hardwood sawmill energy

Process energy use	**GJ m^{-3} kiln dried sawn product**	**Percentage of total**
Thermal energy for drying - wood residues	2.20	78%
Thermal energy for drying – gas	0.025	1%
Electricity	0.50	18%
Energy for mobile plant	0.099	3%
TOTAL	**2.82**	**100%**

Todd *et al* (1998) reported electricity use of 0.12 and 0.84 GJ of electricity per m^3 of sawn product for a small and large Tasmanian hardwood sawmill respectively. Hydro electricity was used. Other hardwood sawmill data was not available for further comparison. In comparison to softwood sawmill energy use, hardwood mills used more electricity per m^3, partly due to the smaller recovery rate and the requirement for sawing. Hardwood mills use less energy per m^3 for drying, in part due to the greater diversity of drying methods (including solar kilns).

4.2.5 Water use in Softwood Processing

Total water use for site and sawmilling and for wood drying was 0.40 kL/m^3 of sawn dried timber.

Water use was 0.051 kL/m^3 sawn green timber for the log yard, debarking, green sawmill and office use and 0.35 kL/m^3 dry sawn timber. Water use in the log yard was relatively small (13% of the total) and is often associated with sprinkling of logs to maintain the moisture content.

Water use in the wood drying process for steam and maintaining moisture content was the main use of water (87%). There was a small range of water use for drying. Of the sample of 8 mills, 2 didn't report and 1 seemed to be an outlier. The remaining 5 samples were 0.39, 0.35, 0.41, 0.36 and 0.24 kL/m^3 of kiln dried product which gave a weighted average of 0.35 kL/m^3. Mains water was reported for all but one site.

CORRIM reports the water usage for Western and Southern US as 0.1 and 0.2 kL/m^3 of dry planed softwood (Milota *et al* 2005 Table 7).

4.2.6 Water use in Hardwood Processing

Total water use for general site and sawmilling and for wood drying was 0.70 kL/m^3 of sawn dried timber.

Water use was 0.42 kL/m^3 sawn green timber for the log yard, debarking, green sawmill and office use. Water use in the log yard was relatively large (60% of the total) and is normally associated with sprinkling of logs to maintain the moisture content. There was a large variation from 0-0.71 kL/m^3 of log input. Six of the samples were clustered in the range of 0.1 – 0.26 kL/m^3 of log input which balanced the high and low values and was reflected in the production weighted average of 0.15 kL/m^3 of log input. This value was then multiplied by the recovery rate to give a water usage per m^3 of sawn green timber.

Water use in the wood drying process was 0.28 kL/m^3 dry sawn timber (40% of the total). There was a very large range of water use for wood drying with many mills reporting no water use or minimal water use. Mill reporting water use were not clustered in the same way as other water use but spread across a large range from 0.16 to 1.7 kL/m^3 of dried timber product. Most mills sourced water from mains supplies. However, there was a diversity of other supplies also reported including on-site dams and bores. The large range in water use may reflect the wide range in practice and reporting.

Todd *et al* (1998) reported 0.46 and 1.7 kL/m^3 of sawn wood product for a small and large hardwood mill in Tasmania. However, it was noted that it was not clear how much of the large mills water was recycled, suggesting this may be an overestimate.

4.2.7 Softwood air emissions

The wood drying process is the main source of air emissions due to fuel combustion to dry the wood as well as emissions released from the wood as it was dried.

The carbon dioxide emissions reflect the energy use and type (Table 28). Approximately 414 kg of CO_2 equivalent (CO_2-e) emissions were generated from the combustion of wood fuel for each 1m^3 of sawn dried wood product. This emission is balanced by the CO_2 absorbed during the growth of the tree in the forest, resulting in a net zero CO_2 emission. The relatively small use of electrical energy has a large effect on CO_2 emissions, accounting for approximately 21% of CO_2 equivalents for producing kiln dried sawn timber because of the range of emission factors.

Combustion of gas as well as fuel for mobile plant also produced combustion emissions such as carbon dioxide as well as energy for electricity. There was also a range of other emissions which are small in quantity but potentially important from a health perspective. These arise from fuel combustion as well as from the timber as it was dried.

Table 28 On-site carbon dioxide emissions for softwood sawmills

	Energy m^{-3} dried sawn product (GJ)	Emission factor (CO_2e kg/GJ) (a)	CO_2e kg m^{-3} dried sawn product	Percentage
Wood fuel	2.50	166 (b)	414	72%
Gas	0.58	60	35	6%
Electricity	0.36	330	119	21%
Automotive Diesel Oil	0.099	75	7	1%
Total			**575**	**100%**

a National Greenhouse Accounts (NGA) Factors, Department of Climate Change (2008)
b See section Carbon dioxide emissions from wood burning

In comparison, CORRIM reported approximately 258 and 353 kg CO_2-e /m^3 of dried sawn product for western and southern regions of the US respectively (Table 8 Milota *et al*, 2006).

4.2.8 Hardwood air emissions

The wood drying process is an important source of air emissions due to fuel combustion to dry the wood as well as emissions released from the wood as it was dried.

The carbon dioxide emissions reflect the energy use and type (Table 29). Approximately 365 kg of CO_2-e emissions were generated from the combustion of wood fuel for each 1m^3 of sawn dried wood product. As for softwood, this emission is balanced by the CO_2 absorbed during the growth of the tree in the forest, resulting in a net zero CO_2 emission. The relatively small use of electrical energy has a large effect on CO_2 emissions, accounting for approximately 31% of CO_2 equivalents for producing kiln dried sawn timber because of the range of emission factors.

Table 29 On-site carbon dioxide emissions for hardwood sawmills

	Energy m^{-3} dried sawn product (GJ)	Emission factor (CO_2e kg/GJ) (a)	CO_2e kg m^{-3} dried sawn product	Percentage
Wood fuel	2.20	166 (b)	365	68%
Gas	0.025	60	2	0%
Electricity	0.50	330	165	31%
Automotive Diesel Oil	0.099	75	7	1%
Total			**539**	**100%**

a National Greenhouse Accounts (NGA) Factors, DCC (2008)
b See section Carbon dioxide emissions from wood burning

Combustion of gas as well as fuel for mobile plant also produced combustion emissions such as carbon dioxide as well as energy for electricity. There was also a range of other emissions which are small in quantity but potentially important from a health perspective. These arise from fuel combustion as well as from the timber as it was dried.

4.2.9 Softwood and hardwood water emissions

Data for water emissions was limited to detailed monitored data from one large Australian softwood sawmill and so may not be representative of the industry. This particular sawmill captured and treated all water emissions from the log yard as well as the kiln drying process. Many mills simply use a trade waste license to release any captured waste water streams to the sewer. Nonetheless, the detailed monitored data provides an indication of water emissions that would otherwise not be monitored and treated on-site.

Most Biological Oxygen Demand (BOD) and suspended solids were generated by the log yard[2]. These emissions are linked to the amount of rainfall and so vary throughout the year. The wood drying emissions were related to kiln condensate and boiler blow-down and are directly related to production. These emissions were captured in detail. When comparing the results of the current study with those of CORRIM, the BOD is much higher in the FWPA study while suspended solids and oil and grease is much lower.

Data reported by Todd *et al* (1998) for water discharged from a large hardwood mill in Tasmania gave average values of pH 7.45; BOD 5mg/L; conductivity of 285 uS/cm and oil and grease of 1mg/L. These values are comparable to the data reported for this study. However, Todd *et al* (1998) note that waste water is only discharged to the river when the waste water dam overflows and the amount was variable making it difficult to estimate a total load.

4.2.10 Softwood and hardwood solid waste

All mills noted that all of the log entering the mills was used and there was no waste. Other solid waste data was based on detailed reporting from one mill and may not be representative of the industry as whole. Waste of 8.7 kg m^{-3} of dried product of kiln boiler ash was reported and noted to be used by the landscape industry. Sludge from the on-site water treatment for site runoff and kiln water emissions was 3.3 kg m^{-3} of sawn wood product. Steel and oil were also reported and noted to be recycled.

4.2.11 Carbon dioxide emissions from wood burning

The collected data is based on actual wood volumes reported for use as fuel for wood drying. This captures process dynamics directly without the need to assume boiler types and efficiencies. The volume of wood burnt was then multiplied by a modified emission factor from the Department of Climate Change (2008).

The modified emission factor was 166 kg CO_2 per GJ of green wood fuel with a calorific value of 9 GJ per tonne. This was similar to the emission factor used in CORRIM of 151 kg CO_2/GJ of steam delivered (p52 Table 2, Milota *et al*, 2005). The carbon dioxide emissions are sensitive to the net calorific value of the wood fuel which is burnt, which in turn is dependent on the moisture content. The moisture content of the wood fuel may vary and mills that use dry wood fuel will produce much less carbon dioxide for the same amount of energy delivered to dry the timber.

The carbon dioxide emissions from burning wood fuel at the sawmill are balanced by carbon sequestration of the wood fuel during the forestry stage of the life cycle.

4.2.12 Other air emissions for kiln drying

Other air emissions for wood drying are based upon McDonald *et al* (2002) and applying National Pollutant Inventory (NPI, 2002) emission factors for wood combustion as well as NPI facility reports. McDonald *et al* (2002) present detailed data for emissions released from timber as it is dried. The NPI data complements this data by presenting emissions from the combustion of wood fuel. Additional emissions are provided from the NPI data for facilities for softwoods where the type of pollutant is not captured in the NPI emission factors.

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[2] For more information refer to p12 Buckman Laboratories 2006 First Flush Treatment Plant (FFTP) Status and Upgrade in Appendix 3 EnviroRisk (2006) Weyerhaeuser Tumut Sawmill Production Increase Environmental Impact Statement.

4.3 Veneer, plywood and LVL

The results here are for an Australian average Veneer, Plywood and LVL using weighted averages of the Plywood and LVL mills surveyed based on total inputs and outputs to the system boundary. The mass balances were checked using SimaPro.

4.3.1 Material inputs

The main inputs considered in the LCI analysis are the logs from forest into the veneer process, leading to veneer input into the plywood and LVL process. The logs were green and include wood and bark. The veneer was mainly taken from the veneer process as dry veneer, but there is also dry veneer imported into both the plywood and LVL process. A unit process approach was used for analysis of veneer, plywood and LVL, whereas CORRIM used a unit process approach for plywood and a black-box approach for LVL.

The input, output and emissions tables for veneer, plywood and LVL contain accumulative cradle-to-gate values. The main inputs to manufacture 1m^3 of average Australian plywood are listed in Table 30 and include energy to produce veneer.

Table 30 Inputs to produce 1 m³ average Australian plywood including energy from veneer production

Material Inputs	**Quantity**	**Unit**
Veneer from veneer process	0.92	m^3
Purchased veneer		
Phenol Formaldehyde Adhesive	53.60	kg
Urea Formaldehyde Adhesive	0.06	kg
Flour	5.60	kg
Filler	3.97	kg
Phenolic Overlay sheets	10.70	kg
Acrylic Putty	0.58	kg
Phenol Formaldehyde Putty	0.20	kg
Paint	0.475	kg
Ink	0.013	kg
Preservatives	0.059	kg
Plastic	0.24	m^2
Strapping	0.15	kg
Total Energy including veneer production		
Electricity	155.80	kWh
Natural Gas	466.00	MJ
LPG	3.37	l
Hogged Fuel	7168.00	MJ
Mains Water	328.00	l

The inputs to produce 1 m³ of veneer include: 2.3 m^3 hardwood and softwood green logs (including bark, sapwood and cores). The inputs to produce 1 m^3 of plywood include: 0.92 m^3 veneer while for 1 m^3 of LVL 0.93 m^3 veneer was used.

Material inputs other than timber to produce 1 m^3 of plywood include 53.6 kg phenol formaldehyde adhesive; 60 g urea formaldehyde adhesive; 5.6 kg flour; 4.0 kg filler; 10.7 kg phenolic overlay sheets; 0.58 kg acrylic putty; 0.02 kg phenol formaldehyde putty; 0.11 l paint; 0.076 l ink; 0.24 L preservatives; 0.017 kg plastic; 0.15 kg strapping. 1 m^3 of LVL consumed 53.6 kg phenol formaldehyde adhesive; 60 g urea formaldehyde adhesive; 5.6 kg flour; 3.97 kg filler; 0.58 kg acrylic putty; 0.02 kg phenol formaldehyde putty; 0.11 L paint; 0.076 L ink; 0.24 L preservatives; 0.017 kg plastic; 0.15 kg strapping.

The recovery rates in Australia are lower than that found in the CORRIM study with yield being 44% compared to 50% estimated by CORRIM. The recovery rate of wood is variable, with small labour intensive mills reporting lower recovery rates. The individual mill recipes for adhesives varied considerably and in comparison to CORRIM data, the Australian mills used double the amount of adhesive per m^3 of plywood.

4.3.2 Energy

There are numerous sources of energy used to produce veneer, plywood and LVL. Energy input into the process includes electricity, natural gas, liquid propane gas (LPG), diesel and wood fuel.

155.8 kWh of electricity is used in all the processes to operate the manufacturing machinery to produce 1 m^3 of plywood and the supply was based on the Australian electricity grid averages, weighted by overall state based consumption. The distribution of electricity was by unit process and was obtained using input from a survey of experts.

466 MJ of natural gas is used in drying of veneer and heat generation.

3.37 L of LPG is used in forklift trucks which are used to move veneer, plywood and LVL around the mill.

1.5 L of diesel is used in log loaders which are used in the veneer preparation unit process only which means all diesel is assigned to this process.

Energy use was higher than recorded by CORRIM with small mills being at the extremes of efficiency (i.e. both more and less efficient).

7168 MJ of energy from waste wood is used in the process as fuel in the furnace mostly for drying in all mills.

4.3.3 Water

328 L of water is used to produce 1 m^3 of plywood and is predominantly from mains water, with some mills utilising rain water, dam and river water. Four mills claimed to use dam or river water during site visits, but data provided indicated mains volume. The impact of these other water sources is small and the data hard to confirm so mains supply was used as a default. With the focus on limiting water use in manufacturing all mills are looking at recycling their water during processing. Recycled water is not shown in the model.

4.3.4 Transportation

Transportation of logs and adhesives was considered to be by articulated 30 tonne truck. The delivery of the logs is included in forestry products and not within the system boundary of the veneer, plywood and LVL products. Delivery of all other material inputs is by rigid truck which is deemed to be 8 tonne capacity carrying out a task with a full load for delivery and a 10% return load. As the transport impact was large relative to the other processes in the first trial model, the distances were important and needed to be specific to ensure correct relative impact. Delivery distances were calculated by a weighted average of tonnage freighted by distance travelled.

4.3.5 Emissions

The most significant emission factor was due to the boiler. This accounted for almost half of the emissions from the system for LVL and plywood and about 60% for veneer. The total environmental impact for plywood per cubic metre as measured by Eco-indicator 99 was very similar to those for LVL.

4.3.6 Outputs

The product outputs from this system are veneer, plywood and LVL which are high value products. There is a large range of plywood and LVL products ranging from veneer through interior, exterior, formwork and structural plywood to tongue and groove flooring, with many thicknesses and number of plies.

The outputs from 1 m^3 input logs include 239 kg dry veneer, which is the main input to the plywood and LVL processes. The waste products from the plywood and LVL processes are minimal and are thus included in the veneer outputs. Other outputs include: 80 kg chips (sold); 139 kg chips (used); 61 kg cores (sold); 8 kg cores (used); 15 kg bark; 55 kg sawdust;

13 kg wood-waste; 321 kg water loss; 53 m^3 dry chip (used); and 44 kg unaccounted for wood waste.

4.3.7 Comparison with other sources

The inputs per 1 m^3 of Australian and CORRIM Pacific north west (PNW) plywood and LVL are shown in Table 31. Log inputs are remarkably similar but Australian production uses about 30% more adhesive. Electricity usage is a little less for plywood but similar for LVL. The total energy for Australian plywood is about 55% higher than that for PNW plywood due to much greater use of hogged fuel. The mains water usage is low with PNW plywood using about 40% more than for Australian plywood and PNW LVL using about 17% less than Australian LVL. The higher total energy use for Australian plywood results in a much larger global warming impact (essentially CO_2-e) (Table 32).

Table 31 Comparison of Inputs to produce 1m^3 Australian plywood, PNW plywood, Australian LVL and PNW LVL

Inputs	Plywood		LVL		
	FWPA LCI	CORRIM (PNW)	FWPA LCI	CORRIM (PNW)	Units
Material Inputs					
Logs (green) including bark, sapwood, cores	2.11	2.10	2.12	2.10	m^3
Phenol Formaldehyde Adhesive	71.60	54.86	71.60	54.86	kg
Energy					
Electricity	468.40	565.00	468.40	446.00	MJ
Natural Gas	734.00	3201.88	734.00	406.00	MJ
LPG	78.98	402.00	78.98	12.00	MJ
Hogged Fuel	7710.00	1808.30	7710.00	NA	MJ
Diesel	399.86	65.23	399.86	14.00	MJ
Mains Water	344.00	481.28	344.00	285.40	l

Table 32 Comparison of CO_2 emissions for 1m^3 Australian plywood, PNW plywood, Australian LVL and PNW LVL

Impact category	Plywood		LVL		
	FWPA LCI	CORRIM (PNW)	FWPA LCI	CORRIM (PNW)	Units
Global Warming	757	323	676	606	kg CO_2

4.4 Particleboard and MDF

The results in this study are for an Australian average particleboard and MDF, using weighted averages of the particleboard and MDF mills surveyed based on their annual production volumes. Mass balances for all inputs and outputs into the particleboard and MDF products were undertaken as part of the data quality check, although they are difficult to establish for these processes. The inputs to produce particleboard and MDF are summarised in Table 33 and Table 34. Wood weight is given in Bone Dry Tonnes (BDT).

Table 33 Inputs to produce 1m^3 of particleboard

Inputs	Amount	Units
Material Inputs		
Wood chips (BDT)	386.9	kg
Wood shavings (BDT)	150.5	kg
Saw dust (BDT)	112.0	kg
Softwood pulp logs (BDT)	71.67	kg
Adhesive	65.04	kg
Wax	9.85	kg
Ancillary materials		
Water consumption	213	Litres
Other consumables (sander belts, saw blades, etc.)	4.25	AU$
Energy Inputs		
Electricity	145.61	kWh
Natural Gas	722.29	MJ
Diesel	15.95	MJ
Fuel oil	85.65	MJ
LPG	63.56	MJ
Biomass residues	1,549.33	MJ

Table 34 Inputs to produce 1m^3 of MDF

Inputs	Amount	Units
Material Inputs		
Wood chips (BDT)	612.75	kg
Softwood pulplog (BDT)	167.57	kg
Adhesive	73.81	kg
Wax	7.14	kg
Ancillary materials		
Water consumption	822.29	Litres
Other consumables (sander belts, saw blades, etc.)	5.27	AU$
Energy Inputs		
Electricity	364.91	kWh
Natural Gas	1,326.81	MJ
Diesel	26.36	MJ
LPG	8.29	MJ
Biomass residues	2,577.95	MJ

4.4.1 Material Inputs

The main inputs considered in the LCI analysis of particleboard and MDF products are the wood fibre inputs, adhesives and wax; and small quantities of paints and inks, preservatives, strapping and plastic for packaging and ancillary materials (sanding paper, saw blades, etc.) with the three main inputs being wood fibres, adhesives and wax. Wood fibres are obtained from a variety of sources (chips, shavings, sawdust, dockings) and tree species (mainly Radiata Pine and Hoop Pine softwood in Australia). The type and quantity of adhesive (urea-formaldehyde, melamine-formaldehyde, phenol formaldehyde) and wax are important factors in establishing the required characteristics of particleboard and MDF products.

The average material inputs into 1m^3 of particleboard are 387 bone dry (B.D) kg of woodchips, 72 B.D kg of softwood pulp logs, 151 B.D kg of wood shavings, and 112 B.D kg of sawdust. The average inputs into 1m^3 of MDF are 612 B.D kg woodchips and 168 B.D kg softwood pulp logs.

These data have been combined with product specific information on thickness and end use of the product (normal, moisture resistant and flooring). Specific adhesive type and quantity, and wax quantity, is dependent on specific product information, although as an approximation 1m^3 of particleboard uses 65 kg of adhesive and 9.9 kg of wax, while 1m^3 of MDF utilises 74 kg of adhesive and 7.1 kg of wax.

Both particleboard and MDF can be laminated on the same production line. The material inputs for the lamination on both sides of 1m^2 of both particleboard and MDF are 0.177 kg paper, 0.221 kg UF adhesive, and 0.2148 kg MF adhesive.

4.4.2 Energy

There are numerous sources of energy used to produce particleboard and MDF. Energy input into the process includes electricity, biomass (wood waste), natural gas, liquid propane gas (LPG) and diesel. Electricity is used in all the processes to operate the manufacturing machinery and the supply was based on the Australian electricity grid averages, weighted by overall state based consumption.

Process waste (rich in biomass) and in some cases woodchip fuel is used in the boiler process. The heat and steam generated is used to dry fibres and heat (oil used in) the press. Natural gas is sometimes used as a fuel if there is not enough biomass waste for the boiler. LPG and diesel are used in small amounts in forklift trucks which are used to move particleboard or MDF around the mill.

To manufacture 1m^3 of particleboard, the average energy requirements are 145.6 kWh of electricity, 1,549.3 MJ of biomass energy, 722.3 MJ of natural gas, 16.0 MJ of diesel, 85.7 MJ of fuel oil, and 63.6MJ of LPG.

The manufacture of 1m^3 of MDF requires on average 364.91 kWh of electricity, 2,577.9 MJ of biomass energy, 1,326.8 MJ of natural gas, 26.36 MJ of diesel, and 8.29 MJ of LPG.

The average energy requirements for laminating both sides of 1m^2 of particleboard and MDF are 0.664 kWh of electricity, 2.47 MJ of natural gas, 0.046 MJ of LPG and 0.002 MJ of Biomass.

4.4.3 Water

Water is used as an input into the system and is sourced from both on-site bores and mains water. Most plants recycle process water. Average water use for the manufacture of 1m^3 of particleboard was 213 L, while for the manufacture of 1m^3 of MDF it was 822.3 L.

4.4.4 Transportation

Transportation of timber fibres (peeler logs, woodchips, shavings, dockings, sawdust) and adhesives is considered to be by articulated 30 tonne truck and delivery of all other material inputs is by rigid truck freight task. As the transport impact was significant relative to the other processes the distances were considered important and needed to be specific. Delivery distances and modes were supplied by the mills.

The average transport inputs for the manufacture of 1m^3 of particleboard are 116 t km of road transport for fibre and 45 t km of road transport for adhesive. The average transport inputs for the manufacture of 1m^3 of MDF are 81 t km of road transport for fibre input, and 21 t km of road transport and 497 t km of shipping transport for adhesive. The average transport inputs for the lamination on both sides of 1m^2 of particleboard or MDF are 0.0806 t km for the transport of paper, and 0.21 t km for the transport of adhesive.

4.4.5 Outputs

The product outputs from this system are particleboard and MDF, which are high value products. There is a large range of particleboard and MDF products and not all could be investigated. Co-products include bark, although in some cases this is used as biomass fuel (by-product). By-products include rejected fibres, sanding dust, off-cuts and rejected product. Wastes include dried adhesive and packaging off-cuts (plastic).

4.4.6 Comparison of manufacturing with other sources

Table 35 and Table 36 show a comparison of the values determined from this report with those found in Ecoinvent 2 (Pré Consultants, 2008) and Grant (2005).

Table 35 Comparison of particleboard manufacture with Ecoinvent 2 and Grant data

Inputs	Units	FWPA LCI	Ecoinvent 2[§]	Grant (2005)
Material Inputs				
Wood (BDT)	kg	721	666	776
Adhesive	kg	65	51	67
Wax	kg	9.9	11	7.5
Ancillary materials				
Water consumption	Litres	213	304	160
Energy Inputs				
Total energy input	GJ	2.96	1.80	3.57

[§] Energy inputs under Ecoinvent 2 are lower due to there being no processing of whole logs in the Ecoinvent process, with the only wood input being chips.

Table 36 Comparison of MDF manufacture with Ecoinvent 2 and Grant

Inputs	Units	FWPA LCI	Ecoinvent 2	Grant (2005)
Material Inputs				
Wood (BDT)	kg	780	720	797
Adhesive	kg	73.8	50	47
Wax	kg	7.1	21	5.2
Ancillary materials				
Water consumption	Litres	822	180	1168
Energy Inputs				
Total energy input	GJ	5.25	5.72	6.30

4.4.7 Lamination

Lamination involves the impregnation of paper with a thermosetting adhesive formulation. Melamine is either the only adhesive used or it forms the outer layer of the impregnation to ensure product properties. Adhesive impregnated papers are applied to wood panel sheets in a short cycle hot press. Heat and pressure cause melamine adhesive to flow into the board surface and it cures to a hard plastic finish that is an integral part of the surface, not just adhered to it. The inputs to laminate 1m^2 of board on both sides are shown in Table 37.

Table 37 Inputs to 1m^2 of lamination of particleboard or medium density fibreboard

Inputs	Amount	Units
Material Inputs		
Base paper	0.177	kg
UF Adhesive	0.221	kg
MF Adhesive	0.215	kg
Additives	0.069	AU$
Ancillary materials		
Maintenance	0.0014	AU$
Energy Inputs		

Electricity	0.664	kWh
Natural Gas	2.466	MJ
LPG	0.463	MJ
Biomass residues	0.0018	MJ

4.5 Glulam and engineered I-beams

4.5.1 Material Inputs

On average, 1 m^3 of glulam requires 668 kg of dried sawn timber, 11.1 kg of adhesive (PRF), 0.436 kg of steel strapping and 0.780 kg of low-density polyethylene (LDPE) film for wrapping.

Material inputs for 1 lineal metre of a 280x70mm I-beam made of OSB web with softwood timber flanges are 4.253 kg of softwood timber, 1.429 kg of OSB, 0.050 kg adhesive (PRF), 0.003 kg of steel strapping and 0.002 kg of plastic strapping while 1 lineal metre of a 300x63 I-beam made of plywood web with LVL flanges required 2.985 kg of LVL, 1.291 kg of plywood, 0.027 kg of adhesive (PRF), 0.003 kg of steel strapping and 0.002 kg of plastic strapping.

4.5.2 Energy

On average, to produce 1 m^3 of glulam requires 101.3 kWh of electricity, 95.7 MJ of natural gas, 28.9 MJ of LP gas, 11.2 MJ of diesel and 0.075 kg of lubricant.

Energy requirements were for, 1 lineal metre of a 280x70mm I-beam made of OSB web with softwood timber flanges, 0.517 kWh of electricity and 0.304 MJ of LPG and, for 1 lineal metre of a 300x63 I-beam made of plywood web with LVL flanges, 0.224 kWh of electricity and 0.330 MJ of LPG.

4.5.3 Water

The water requirements to produce 1 m^3 of Glulam are 67.6 litres. 1 lineal metre of all engineered I-beams made either of OSB web with softwood timber flanges or plywood web with LVL flanges requires a negligible amount of water (0.0002 l).

4.5.4 Outputs

Based on the survey results from the financial year 2005-2006, to produce 1 m^3 (540 kg) of glulam, 668 kg of dried sawn timber was required. While producing 1m^3 of glulam, 65 kg of shavings and trimmings and 63 kg of sawdust were generated. The percentage recovery of wood in terms of wood input as sawn timber and output as glulam is 81%.

4.5.5 Comparison to other data sources

The comparison of LCI data illustrates that the project data is within the range of other studies. In some cases, such as timber and electricity used, the data is very similar to other studies. This is most likely because electricity is well measured and the process of manufacturing is reasonably consistent regardless of the location.

Wood recovery for glulam in terms of wood input as sawn timber and output as glulam was estimated to be 81% (Table 38). Thus 19% was allocated to shavings and trimmings and sawdust. CORRIM's data showed a similar average recovery rate of 82% for both PNW and SE regions.

Table 38 Glulam product yields comparison

Wood Mass Balance (weighted average)	FWPA LCI*	CORRIM (PNW)**	CORRIM (SE)***
Input (kg m^{-3})	668	592	676
Output - Glulam (kg m^{-3})	540	483	551
Output – shaving, trimming & sawdust (kg m^{-3})	128+	89	119
Output - wood waste (kg m^{-3})		20	6
Recovery of wood (%)	81%	82%	82%

+Wood waste involved in shaving, trimming and sawdust

*Australian glulam weight averaged

**CORRIM (Pacific North West Area)

***CORRIM (South East Area)

On average, Australian glulam requires 500.6 MJ of energy to manufacture 1 m^3 of product (Table 39). On the other hand, CORRIM's results suggest that US glulam production requires more energy at 893 MJ and 1417 MJ for the PNW and SE regions respectively. As for energy types, Australian glulam consumes more electricity at 365 MJ compared to CORRIM's result (304 MJ for PNW and 356 MJ for SE), but for other energy sources such as natural gas, or diesel, this study shows Australian glulam consumes less.

On average, to manufacture 1 linear metre of Australian I-beam, 2.17 MJ and 1.14 MJ of energy required for the OSB and plywood web products, respectively. On the other hand, CORRIM's results show consumption at 1.1 MJ for PNW and 1.37 MJ for SE.

When comparing total energy consumption for each of the products, electricity consumption is dominant. I-beam with plywood web appears similar to CORRIM's I-beam but the OSB web I-beam consumes twice the energy of the others. This is due, in part, to the different flange material used in the manufacturing process of the Australian OSB web I-beam product. That product requires a flange finger jointing process, which requires extra electricity consumption.

Table 39 Comparison of energy requirements for 1 m^3 of glulam manufacturing (on-site)

Fuel source	FWPA LCI*	CORRIM (PNW)**	CORRIM (SE)***
Electricity (MJ)	364.6	304.0	356.0
Natural gas (MJ)	95.7	153.0	1024.0
LP Gas (MJ)	29.0	41.0	0.0
Kerosene	0.0	0.001	0.0
Diesel (MJ, 36.7MJ/l)	11.2	13.2	24.2
Gasoline (MJ, 32MJ/l)	0.0	2.9	12.5
Hogged fuel (MJ)	0.0	379.0	0.0
Sum (MJ)	500.6	893.1	1416.7
Ratio (%)	100%	178%	283%

*Australian glulam weight averaged
**CORRIM (Pacific North West Area)
***CORRIM (South East Area)

5 DISCUSSION

5.1 Achievements

The forestry and wood products LCI project has achieved the following:

- First forestry and wood products LCI in Australia to include softwood plantation and native hardwood forests.
- First consistent LCI datasets for forestry and wood products that captures a wide range of producers and products across Australia.
- Integration of a wide range of typical forest and wood products used in building into one database.
- Extensive quality assurance and associated documentation procedures, including checklists, generated by the project.
- High quality of data and documentation transparent to the users, including the methods used, references, the manner in which data was collected, compiled and verified, and review and validation by experts.
- A LCI of representative products, which is of high quality, uniformly assessed, credible and independent.

The importance of an Australian forestry and wood products LCI database is in its

- Leadership role among manufactured products
- Potential for guidance to consumers looking for environmental impact of choices of building products.
- Data that can be incorporated into a future national LCI database containing other processes and products.
- Benchmarking of environmental impacts of a wide range of forestry and wood products.

5.1.1 Limitations

The coverage of the forestry and wood products LCI is limited to specified forest types and wood products. In addition, although the data collection captured a large proportion of industry production, it was not a statistical sample for sectors such as sawmills. Any bias in the sample can be assessed when an accurate population frame becomes available.

The available detail on the unit processes which produce the final products is variable. While there is little, if any, impact on the LCIs of the specified products, further sub-division into smaller unit processes for some products would assist manufacturers in more fully understanding the sources of emissions and potential improvements in their processes, from an environmental impact point of view.

5.1.2 Knowledge gaps

This study revealed significant knowledge gaps in terms of the environmental loads and impacts of a variety of forestry-related activities in Australia. One of the most important of these is emissions of non-CO_2 GHGs from slash and fuel reduction burning. At present, data on the volume of residues left or burnt following harvest are not recorded, and non-CO_2 emissions from burning this material are based on international figures which have large uncertainties. Other major sources of GHG emissions which lack data include harvesting, haulage and fertiliser application. Additionally, further studies of CO_2 emissions and storage in soil and litter, non-CO_2 emissions from forest growth and decomposition, emissions from fertiliser and pesticides, and impacts of plantations and native forest management on water supply are required.

5.2 Benefits

The development of a LCI for Australian forestry and wood products is a major step forward in the provision of quality data on the environmental impacts of wood products. The wide forestry and wood industry coverage also makes the LCI database very representative of Australian wood products and an excellent basis for assessing the environmental impacts of any application of wood products.

Collection, enhancement and verification of data provide the industry with reliable environmental impact information to improve environmental performance as well as providing data for future assessment of choice in building products on the basis of environmental impacts. This potentially means greater acceptance of wood as an environmental material choice, give wood products a greater prominence in evaluation tools, and greater understanding by the industry of future growth areas, such as recycling opportunities and take back schemes.

The first national LCI database on Australian forestry and wood products production delivers:

- An objective and quantitative basis for future comparison of competing wood products and non-wood alternatives,
- An objective and quantitative basis for comparing systems which incorporate wood products to those systems which use alternative materials, for example, complex composite products or whole buildings,
- A method of comparing the environmental impacts of wood products from changed production processes,
- An up-to-date database for use with Life Cycle Assessments of Australian wood products and the buildings in which they are used,
- A forestry and wood products LCI which can be incorporated in any future national LCI database together with a range of other building and construction materials to enable full Life Cycle Assessment by industries and producers.
- Facilitating communication of environmental information to customers and other stakeholders,
- Setting a benchmark for carbon sequestration in wood products, and
- Setting an industry standard for handling of environmental data.

6 REFERENCES

ABARE (2003) *Australian Forest and Wood Product Statistics*, March and June quarters 2003, Canberra, November.

ABARE (2006) *Australian Forest and Wood Product Statistics*, March and June quarters 2006, Canberra, November.

ABARE (2007) *Australian Forest and Wood Products Statistics*, September and December Quarters 2006.

Aldentun, Y. (2002) Life cycle inventory of forest seedling production — from seed to regeneration site, *Journal of Cleaner Production* 10, 47-55.

American Forest and Paper Association (1996) Sustainable Forestry Principles and Implementation Guidelines, Washington.

AUB (Arbeitsgemeinschaft Umweltverträgliches Bauprodukt e.V.) (2005) Regeln für AUB Producktdeklarationen, http://bau-umwelt.de/fileadmin/user_upload/PCR/PCR_Holzwerkstoffe.pdf (Accessed 15 February 2008).

Australian Government (2007) Business Roundtable on Sustainable Development http://www.industry.gov.au/content/itrinternet/cmscontent.cfm?objectID=36D93D3A-65BF-4956-B66BEC060380DBC3, accessed 30 January 2008.

Benyon, R. Carlyle, J.C.C. and Doody, T. (2006) Impacts of tree plantations on groundwater in south-eastern Australia. *Australian Journal of Botany* 54: 181–192.

Berg, S. and Karjalainen, T. (2003) Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. *Forestry* 76, 271-284.

Berg, S. and Lindholm, E. (2005a) Energy use and environmental impacts of forest operations in Sweden. *Journal of Cleaner Production* 13, 33-42.

Berg, S. and Lindholm, E. (2005b) Corrigendum. Energy use and environmental impacts of forest operations in Sweden [Journal of Cleaner Production 13, 33-42]. *Journal of Cleaner Production* 13, 327.

Boustead Consulting (2007) http://www.boustead-consulting.co.uk

Boustead, I. (1995) The Boustead Model for LCI Calculations, Vol 1 Data Sheet 1-60, Dec

Boustead, I. (2003) *An introduction to Life Cycle Assessment* Boustead Consulting Ltd.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W. and Vertessy, R.A. (2005) A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, *Journal of Hydrology*, 310, 28–61.

Bubb K.A. and Croton, J.T. (2002) Effects on catchment water balance from the management of *Pinus* plantations on the coastal lowlands of south-east Queensland, Australia, *Hydrological processes*, 16, 1, 105-117.

Built Research Establishment (BRE) (2007) *Environmental Profiles*, UK http://www.bre.co.uk/page.jsp?id=53 (Accessed 15 February 2008)

Consoli, F., *et al* (1993) Guidelines for Life-Cycle Assessment: A 'Code of Practice', SETAC (Society of Environmental Toxicology and Chemistry), Brussels.

Cornish, P.M. and Vertessy, R.A. (2001) Forest age induced changes in evapotranspiration and water yield in a eucalypt forest, *Journal of Hydrology*, 242, 43-63.

CORRIM (2001) *Research guidelines for life cycle inventories* CORRIM, University of Washington, Seattle, WA

CORRIM (2004) (prepared by Wilson, JB, Sakimoto, ET) *Module D Softwood Plywood Manufacturing* Consortium for Research on Renewable Materials CORRIM: Phase 1 Final Report

CORRIM (2004a) (prepared by Wilson, J.B. and Dancer, E.R.) *Module H Laminated Veneer Lumber – Pacific Northwest and South East,* Consortium for Research on Renewable Materials CORRIM: Phase 1 Final Report

CORRIM (2004b) Glued Laminated Beams – Pacific Northwest and Southeast, Phase I Final Report, June.

CORRIM (2005) Life cycle environmental performance of renewable building materials in the context of residential construction, Consortium for Research on Renewable Industrial Materials, (CORRIM, Inc.), 59p.

CORRIM (2008) Annual Report, Life Cycle Inventory of MDF and particleboard is underway: http://www.corrim.org/reports/annual/2006/CORRIMannR092206.pdf (Accessed 15 February 2008).

Demkin, J. A. [Ed.] (1996) *Environment Resource Guide (ERG),* American Institute of Architects, Wiley, United States.

Department of Climate Change (2008). National Greenhouse Accounts (NGA) factors. Updating and replacing the AGO Factors and Methods Workbook

Department of Environment and Heritage (2006a) Emission Estimation Technique Manual for Fugitive Emissions, Department of Environment and Heritage, National Pollutant Inventory, http://www.npi.gov.au/handbooks/approved_handbooks/ffugitive.html, 05 Oct. 2006.

Department of Environment and Heritage (2006b) Appendix 4 – methodology and assumptions for estimating emissions, http://www.deh.gov.au/atmosphere/fuelquality/publications/pubs/summaryapp4.pdf, 05 Oct. 2006.

EcoInvent Centre (2007) http://www.ecoinvent.org/ecospold-data-format/.

Emsol (2005) *Summary of Sawmill Energy Audits* Energy Efficiency and Conservation Authority, New Zealand, http://www.eecabusiness.govt.nz/eib/eib-library/summary/sawmill-energy-audit-summary-06.pdf

Environment Australia (2002) *National Pollutant Inventory Emission Estimation Technical Manual for Timber and Wood Production* 11 January 2002 Version 1.1, Environment Australia, http://www.npi.gov.au/handbooks/approved_handbooks/pubs/timber.pdf (Accessed 15 February 2008).

Forests NSW (2007) Social, environmental and economic report 2006-07. Forests NSW, Sydney.

Forests NSW (2006a) *Facts and Figures 2005-06,* NSW Department of Primary Industries.

Forestry Tasmania (2007) 2007 Annual Report. Forestry Tasmania, Hobart.

FPC (2007) Forest Products Commission annual report 2006-07. Forest Products Commission, WA.

Frank, J. and Stuanes, A.O. (2003) Short-term effects of liming and vitality fertilization on forest soil and nutrient leaching in a Scots Pine ecosystem in Norway. *Forest Ecology and Management* 176: 371-386.

Gifford, J., Ford-Robertson, J., Robertson, K. and Hall, P. (1998) Life Cycle Assessment of Sawn Lumber: Inventory Analysis, Confidential Report, Forest Research, Rotorua, New Zealand.

Grant, T. (2005) Life Cycle Inventory of Laminex Products, for the Laminex Group.

Hall and Janssen (1997) *Kiln Dried Timber*, Department of Commerce, NSW

Harrimann, R. (1978) Nutrient Leaching From Fertilized Forest Watersheds in Scotland. Journal of Applied Ecology. 15: 933-942.

Hong-Kong Housing Authority (2005) Life cycle assessment (LCA) and life cycle costing (LCC) study of building materials and components, http://www.housingauthority.gov.hk/hdw/content/document/en/aboutus/resources/publications/lifecyclereport.pdf (Accessed 15 February 2008).

Howard, N., Edwards, S. and Anderson, J. (1999) BRE methodology for environmental profiles of construction materials, components and buildings, BRE publications, CRC Ltd, London, 65p.

Hunter, I.R. and Hunter, J.A.C. (1991) Apparent phosphorus uptake and change in nitrogen content of *Pinus radiata* growing on soils of different phosphorus retention, treated with superphosphate and A-grade rock phosphate. *New Zealand Journal of Forestry Science* 21: 50-61.

IBIS (2003) *C2311 - Log Sawmilling in Australia*, IBISWorld Pty Ltd.

Ilic, J., Boland, D., McDonald, M., Downes, G. and Blakemore, P. (2000) Woody Density Phase 1 - State of Knowledge National Carbon Accounting System - Technical Report No. 18.

IPCC (2006) *Greenhouse Gas Inventories Reference Manual*, IPCC Guidelines for National Greenhouse Gas Inventories. Volume 3.

ISO 14040 (2006) International Standard ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework, Geneva, Switzerland: International Organization for Standardization.

ISO 14041 (1998) Environmental management – Life cycle assessment - Goal and scope definition and inventory analysis. Geneva, Switzerland: International Organization for Standardization.

ISO 14044 (2006) International Standard ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines, Geneva, Switzerland: International Organization for Standardization.

ISO/TS 14048 (2002) International Standard ISO 14048 (Technical Specifications): Environmental management – Life Cycle assessment – Data documentation format, Geneva, Switzerland: International Organization for Standardization.

Jenkin, B.M. and Tomkins, B. (2006) The use of chemical pesticides by the plantation forest industry, FWPRDC Project Report, PN06.4016.

Johnson, L.R., Lippke, B., Marshall, J.D. and Comnick, J. (2005) Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States, Wood and Fiber Science, Vol. 37, 30-46.

Kakita, H., Yagita, H., Narita, N., Kato, A., Kimura, M., Aoki, R. and Inaba, A. (2006) "LCI Analysis of a Detached Wooden House", Proceedings of the 7th International Conference on EcoBalance, Tsukuba, Japan, 14-16 November, pp. 263-264.

Karjalainen, T. and Asikainen, A. (1996) Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. *Forestry* 69, 215-228.

Khanna, P.K., Raison, R.J., Falkiner, R.A. Willett, I.R. and Connell, M.J. (1992) Effects of N P K fertilisation on the chemistry of a yellow podzolic soil under *Pinus radiata*. *Forest Ecology and Management* 52: 65-85.

Lawson, B. (1996) Building Materials Energy and the Environment. Towards Ecologically Sustainable Development, The Royal Australian Institute of Architects.

Lee, K. H. and Jose, S. (2005) Nitrate leaching in cottonwood and loblolly pine biomass plantations along a nitrogen fertilization gradient. Agriculture, Ecosystems & Environment 4: 615-623.

May, B.M., Carlyle, C.J. (2005) Nitrogen Volatilisation From Urea Fertiliser in Mid-Rotation Pinus Radiata Plantations in South-Eastern Australia, *Australian Forestry*, 68: 20-26.

McDonald, A. G., Dare, P. H., Gifford, J. S., Steward, D., Riley, S. (2002) *Assessment of air emissions from industrial kiln drying of Pinus radiata wood*. Holz als Roh- und Werkstoff 60 (2002) 181–190, Springer-Verlag 2002.

MBAC (2004) *Potential wood flows, technical and scale issues and identification of sustainable management criteria, Report 3*. MBAC Consulting for the National Association of Forest Industries

Milota, M. R. (2004) *CORRIM Phase I Final Report Module B Softwood Lumber – Pacific Northwest Region*, Consortium for Research on Renewable Industrial Materials.

Milota, M., West, C., Hartley, I. (2005) Gate-To-Gate Life-Cycle Inventory Of Softwood Lumber Production, *Wood and Fiber Science,* 37 CORRIM Special Issue, pp. 47 – 57, http://www.corrim.org/reports/.

Mitchell, P (2004) *Life Cycle Thinking (LCT) Implementation: A new approach for 'greening' industry and providing supply chain information: A Plywood Industry Study*, Doctoral Thesis, University of Queensland

Moran, R.J., O'Shaughnessy, P.J., 1984. Determination of the evapotranspiration of E. regnans forested catchments using hydrological measurements. Agricultural Water Management 8, 57-76.

National Pollutant Inventory (NPI) (2002) *National Pollutant Inventory Emission Estimation Technical Manual for Timber and Wood Production 11 January 2002 Version 1.1,* Environment Australia, http://www.npi.gov.au/handbooks/approved_handbooks/pubs/timber.pdf

National Renewable Energy Laboratory (NREL) (2007) *U.S. Life Cycle Inventory (LCI) Database*, May 2007, V 1.4.0. http://www.nrel.gov/lci (Accessed 18 May 2007).

Nebel, B. ands Nielsen, P. S. (2005) LCA Workshop /Roundtable, Rotorua, Forest Research, NZ, February 2005, The International Journal of Life Cycle Assessment, Vol, 10, No. 5, September, pp. 375-376.

Parsons, M., Gavran, M., Davidson, J. (2006) Australia's plantations 2006. BRS, DAFF.

Petersen, A. K. and Solberg, B. (2002) Greenhouse gas emissions, life cycle inventory and cost-efficiency of using laminated wood instead of steel construction. Case: beams at Gardermoen airport, Environmental Science and Policy, 5, 169-182.

Pöyry, J. (1999) *National Carbon Accounting System: Usage And Life Cycle Of Wood Products, Technical Report No. 8* The Australian Greenhouse Office http://www.greenhouse.gov.au/ncas/reports/pubs/tech08.pdf

Pré Consultants (2008) SimaPro, Amersfoort, The Netherlands, http://www.pre.nl/simapro/, accessed 30 January, 2008.

Raison, R.J., Connell, M. J, Khanna, P. K. and Falkiner, R. A. (1992) Effects of irrigation and nitrogen fertilisation on fluxes of soil mineral nitrogen in a stand of Pinus radiata. Forest Ecology and Management 52: 43-62.

Raison, R.J. and Squire, R.O. (2007) Forest Management in Australia: Implications for Carbon Budgets. National Carbon Accounting System Technical Report No. 32. Australian Greenhouse Office, Canberra.

Seppala, J., Melanen, M., Jouttijarvi, T., Kauppi, L. and Leikola, N. (1998) Forest industry and the environment: a life cycle assessment study from Finland, Resources Conservation and Recycling, 23, pp. 87–105.

Sonne, E. (2006). Greenhouse gas emissions from forestry operations: a life cycle assessment. *Journal of Environmental Quality* 35, 1439-1450.

Taylor, J. and Van Langenberg, K. (2003) Review of the Environmental Impact of Wood Compared with Alternative Products Used in the Production of Furniture, Forest and Wood Products Research and Development Corporation, 16p.

Tharumarajah, A., Grant, T., Koltun, P., Park, K., Seo, S. and Tucker, S.N. (2007) Guidelines for developing LCI data for Australian wood products. CSIRO Sustainable Ecosystems report USP2007/32, 50p.

Tharumarajah, A., Park, K., Seo, S. and Tucker, S.N. (2007) LCI data quality assurance and documentation for Australian wood products. CSIRO Sustainable Ecosystems report USP2007/33, 100p.

Todd, J. J. and Higham, R. K. (1996) Life-Cycle Assessment for Forestry and Wood Products Volume 1: Review and Discussion, Forest and Wood Products Research and Development, Queensland, 115p.

Todd, J.J., Higham, R.K. and Grant, T. (1998) Hardwood and Softwood production in Australia., undertaken by University of Tasmania and Centre for Design at RMIT.

Tsuda, K., Murakami, S., Ikaga, T., Kuma, K., Hondo, H. and Narita, N. (2006) "Environmental impact assessment of local structural glued laminated timber based on field survey", Proceedings of the seventh International Conference on EcoBalance, Tsukuba, Japan, 14-16 November, pp. 649-652.

Tucker, S. N., Johnston, D. R., Jones, D. G., Remmers, T. R., Newton, P. W., and Paevere, P. (2005) Environmental assessment of commercial buildings during design using 3D CAD, 2005 World Sustainable Building Conference "Action for Sustainability", Tokyo, Japan, 27-29 September.

USDA (1987) Wood *Handbook - Wood as an engineering material General Technical Report 113.* Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory (http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.htm) (accessed 15 February 2008).

VAFI (2007) Greg McCormack, President, Victorian Association of Forest Industries http://www.vafi.org.au/about-us/president.php, accessed 6 June 2007.

Vertessy, R.A., Watson, F.G.R., O'Sullivan, S.K. (2001) Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecology and Management 143, 13-26.

VicForests (2007) VicForests annual report 2007. VicForests, Victoria.

Wilson, J.B. (2005) "Documenting the environmental performance of wood building materials", Wood and Fiber Science, Vol. 37, pp. 1-2 and all other papers in this CORRIM Special Issue.

Woodard, A. and Grant, T. (2008) Developing the Australian Lifecycle Inventory (AusLCI), http://www.sustained.com.au/index.php?option=com_content&task=view&id=656&Itemid=29, accessed 30 January, 2008.

Ximenes, F.A. and Gardner, W.D. (2004) *Recovery of biomass as green sawn boards after milling of spotted gum (Corymbia Maculata) sawlogs from NSW South Coast*, Forests Science and Research Division – NSW Dept. of Primary Industries, Report for the Australian Greenhouse Office.

Zhang, L., Dawes, W.R. and Walker, G.R. (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 37: 701–708.

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