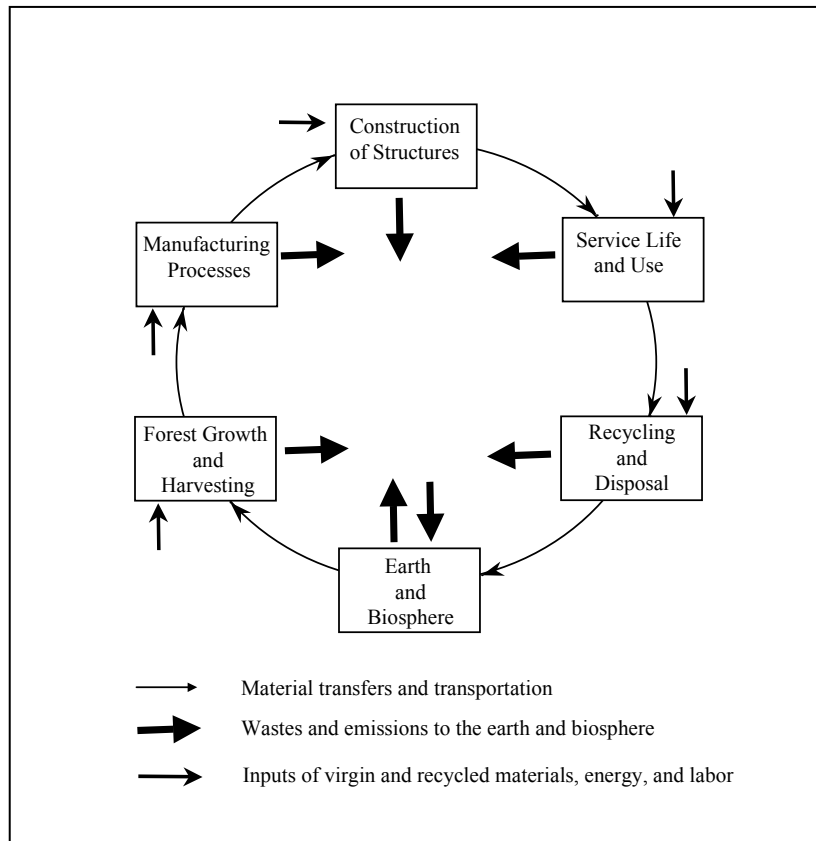


# Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Construction



## PHASE I RESEARCH REPORT ON THE RESEARCH PLAN TO DEVELOP ENVIRONMENTAL-PERFORMANCE MEASURES FOR RENEWABLE BUILDING MATERIALS WITH ALTERNATIVES FOR IMPROVED PERFORMANCE

REVISED AUGUST 2, 2005

Consortium for Research on Renewable Industrial Materials  
(CORRIM, Inc.)



# LIFE CYCLE ENVIRONMENTAL PERFORMANCE OF RENEWABLE MATERIALS IN THE CONTEXT OF RESIDENTIAL BUILDING CONSTRUCTION

## Consortium for Research on Renewable Industrial Materials

October 28, 2004  
Revised July 20, 2005

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# **Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Construction**

**PHASE I RESEARCH REPORT**

## ***EXECUTIVE SUMMARY***

### **Consortium for Research on Renewable Industrial Materials (CORRIM, Inc.)**

This report is prepared with financial support from the USFS (JV11111169-156) and contributions from a number of private companies based on a research plan developed for the Department of Energy (DOE Agreement No. DE-FC07-96ID13437) as a part of the American Forest and Paper Association's Agenda 2020 priorities. Any opinions, findings, conclusions, or recommendation expressed in this publication are those of the authors and do not necessarily reflect the view of the financially contributing entities.

**This report was first published electronically on October 28, 2004 as a review draft.**

**A formal review is included in this revised version: August 2, 2005**

# **LIFE CYCLE ENVIRONMENTAL PERFORMANCE OF RENEWABLE BUILDING MATERIALS IN THE CONTEXT OF RESIDENTIAL CONSTRUCTION**

## **PREFACE**

This report presents results from research conducted under the Phase 1 research plan. This research develops a database and modeling capability to adequately describe the environmental performance of building materials and their uses. The research analyzes key wood materials such as lumber, plywood, composite panels and other structural wood derived products, and provides environmental and economic data on all Life Cycle stages from planting and growing the renewable raw material, manufacture of product, design and construction of buildings, occupation and use through final demolition. The collection of all input and output data is referred to as the Life Cycle Inventory (LCI) for the activity. The data and subsequent analysis follows consistent definitions and collection procedures for the development of LCI profiles for each product and region and to facilitate the integration of results across the full life cycle of material processing and use in order to address environmental performance questions. The ultimate use of LCI information is to analyze it for risk implications on human or ecological health and how the risk can be lowered. This assessment process is referred to as Life Cycle Assessment (LCA).

The Phase I report covers 5 of the 22 modules as described in the original research plan developed for the Department of Energy and the American Forest and Paper Association under Agenda 2020 priorities for pre-competitive research needs. In 1998, the Consortium for Research on Renewable Industrial Materials (CORRIM), with the financial support of its 21 institutional and company members and the Department of Energy developed (1) a research plan, (2) a *Data, Standards and Procedures: Guideline for LCI Analysis*, and (3) an organizational structure to conduct the research plan. This Phase I research plan was designed to pilot-test the collection of data and their analysis for each stage of processing. Implementation of the research plan has led to the development of LCI data for the primary wood producing regions of the US and its analysis. The Phase I research focuses on forest resources from the US Southeast and Pacific Northwest and residential construction in a warm climate (Atlanta) and a cold climate (Minneapolis). The USFS Forest Products Laboratory, 14 research institutions and 10 companies contributed financial support.

This report updates an interim report that was published in March of 2002. The research described in the interim report tested procedures and analyzed data collected for the life cycles of various wood products. Collecting and formatting LCI data for a large number of products is a complex and data intensive task. The process of completing the interim report acted as a mid-course progress report, and allowed a number of internal and external technical reviews that identified areas where improvements were necessary for this final Phase I report. This document, in addition to providing the LCI and LCA for residential construction, addresses questions that arose during the research and provides more complete product coverage. One of the more substantive impacts of this research effort has been the enhancement of institutional capabilities to support the development of environmental performance data and analysis.

The report is organized as follows. Major points are introduced in the executive summary. Section 1 provides the background, mission, organization of effort and objectives. It also provides a summary of the review process including peer reviews by noted international experts to ascertain conformity with ISO 14040, the international standard for LCI/LCA. Section 2 describes the LCI and LCA framework. Section 3 provides a process description of what was accomplished in Phase I. Section 4 summarizes energy use across all stages from forest regeneration to building disposal. Section 5 summarizes the carbon pools across the life cycle of a building including carbon in the forest and products. Section 6 summarizes important raw material efficiency impacts. Section 7 summaries some of the more obvious opportunities to improve environmental performance. Appendix A to the main report provides the checklist on the degree of conformity to LCI/LCA standards provided by external review. The findings for each stage of processing are reported in 15 modules (Modules A-O). Modules A-H are stand-alone LCI reports for intermediate products. Module I provides the construction design for residential building shells and their corresponding bill of materials. Module J uses the bill of materials, wood product LCIs from previous modules and LCIs from alternative materials to integrate across the product LCIs and construction activities. Module J also estimates intermediate environmental risk indices from the LCI data analysis providing a Life Cycle Assessment. Modules K-M characterize the use, maintenance and disposal phases of the life cycle of the building. Module N provides an integrated carbon analysis for the forest growth phase and the life cycle of products, a time series perspective showing how it differs from a life cycle perspective. Module O addresses the impacts of forest management on forest ecology for the Pacific Northwest. Sensitivity analysis is provided for forest management alternatives and various process change issues within each module for perspective on where improved performance might be most productive.

## **EXECUTIVE SUMMARY**

### **BACKGROUND AND STUDY OBJECTIVES:**

The Consortium for Research on Renewable Industrial Materials (CORRIM) is a non-profit organization supported by 15 research institutions for the purpose of updating and expanding a 1976 landmark study by the National Academy of Science on the energy implications of producing and using renewable building materials. We use the same CORRIM acronym as the 1976 study, which was managed by a committee of scientists.

We address an expanding list of environmental-performance issues that has gained considerable attention since the 1976 CORRIM study. No attempt has been made to update or extend the 1976 study, or to include environmental issues not addressed in the original study until this effort was undertaken. Our effort provides a Life Cycle database and performance measures, which can be used to formulate public policy affecting renewable materials industries. Our database is useful for companies to develop strategic investment plans that could improve their environmental performance.

This study's objectives are:

- To create a consistent database of environmental performance measures associated with the production, use, maintenance, re-use, and disposal of alternative wood and non-wood materials used in light construction, i.e., from forest resource regeneration or mineral extraction to end use and disposal, thereby covering the full product Life Cycle from “cradle to grave.”
- To develop an analytical framework for evaluating Life Cycle environmental and economic impacts for alternative building materials in competing or complementary applications so that decision-makers can make consistent and systematic comparisons of options for improving environmental performance.
- To make source data available for many users, including resource managers and product manufacturers, architects and engineers, environmental protection and energy conservation analysts, and global environmental policy and trade specialists.
- To manage an organizational framework to obtain the best scientific information available as well as provide for effective and constructive peer review.

This document is intended to be used as a reference source that contains the databases and analytical framework for those interested in the LCI and LCA for environmental performance of building materials. Its intent is to provide the reader with an explanation of the data and methods used in LCI and LCA. In various places we have demonstrated the use of such data using the LCA approach. There are many shorter papers that can be written on impact assessment based on the information contained in this report such as environmental improvement analysis. The report demonstrates a number of sensitivities through the analysis of alternative scenarios, and additional reports can be written based on the data and methods presented here.

To ensure that the databases established in this report were recognized and accepted, strict international protocols conforming to ISO 14040 standards produced by the International Organization for Standardization were followed throughout the planning, data collection, analysis, reporting and review process.

## PRIMARY AND SECONDARY DATA SOURCES

Data on all inputs and outputs associated with the production of lumber, plywood, oriented strandboard (OSB), glulam, laminated veneer lumber (LVL) and I-joists were collected through surveys of a range of mill types within processing regions. Growth and yield models representing conditions in the Pacific Northwest and Southeast growing regions and recent studies of harvesting activities were used to gather forest regeneration, growth and log production data. The most difficult aspect of our data collection was to maintain consistency across many products made from different processes and wood species. Product characteristics vary substantially, as do the measurement practices used by different producers. We conducted analyses of mass and energy balances for each processing stage in order to provide a validity check on the data quality. Different measurement conventions and imprecise measurement of characteristics such as moisture content can contribute to mass and/or energy imbalances making additional data collection necessary. We compared different mills in the same region and analyzed the differences across regions. In selected cases, such as the unit process for boilers (the conversion of biomass to energy), and softwood green lumber, additional data was collected for the final report to improve the sample size and resolve mass balance discrepancies.

The data collected were used to construct Life Cycle Inventories (LCIs) for the various wood products i.e. measures of all inputs and outputs across each stage of processing. These LCIs were incorporated into the ATHENA™ Environmental Impact Estimator model (EIE). The EIE model provides LCI measures for a completed building based on the bill of materials developed for the US house designs and the LCI data that was developed for each US wood product. The EIE also contains LCIs for non-wood materials used in construction. The ATHENA™ Institute, a Canadian research institute and cooperator on the project, then proceeded to analyze the architectural designs for the representative residential structures and corresponding bill of materials. The analysis indicated that many similar materials are used in the construction of residential wood and non-wood structures for a cold climate (Minneapolis) and a warm climate (Atlanta). In other words, a wood-framed house has many non-wood materials used in its construction.

An objective of the research is to analyze the product life cycle from planting and growing the renewable raw material to final demolition of the house. To do so we need to assign burdens on building materials so that a sensitivity analysis for forest management alternatives on forest ecology can be performed. In the United States, a little over half of the wood produced in the forest is used directly in construction. The environmental burdens from the production processes used to produce building materials were allocated according to the mass of materials used in each unit process for producing products and then for the mass of products used in building construction. Allocation of burdens at the unit process level results in the energy for drying being charged only to products that were dried. Since drying energy is quite dominant in the production of wood, there is relatively little energy assigned to co-products. Burdens were allocated to co-products such as the chips used to make paper based on their mass share at the stage of processing they were generated. Similarly, the burden accumulated from transportation, processing energy, and construction energy was allocated to the building according to the mass of materials used in building construction. The environmental impacts from energy uses are derived from national or regional grids of purchased electrical energy and fossil fuels. Thus the environmental burdens derived from energy consumption are allocated according to the specific type of energy consumed (11 types) and its place of origin (raw material and manufacturing producing regions and construction regions).

In this study, many emissions are reported for each stage of production (extraction, manufacturing, transportation) with the most important being carried forward to the building construction stage. For the construction stage sixteen different air emissions are identified, and twenty-three different sources of water emissions are identified with manufacturing. Six categories of solid waste are tracked for all production stages. Vital stand structure measures of the forestland environment are also tracked to describe their effects on water, habitat, carbon and biodiversity, several of which require landscape-wide measures to be useful. These complex arrays of environmental outputs for the construction of a residential building are reduced to environmental performance indices to simplify the communication of findings. However, the science behind best weighting schemes to represent aggregate environmental risk indices for water, air, solid waste, global warming potential, and forest health is still evolving, and in certain cases may be controversial and beyond the scope of this Phase 1 report.

## **ENVIRONMENTAL PERFORMANCE INDEX COMPARISONS FOR RESIDENTIAL BUILDING CONSTRUCTION ALTERNATIVES**

The ATHENA™ Institute derived indices for water and air emissions, solid waste, and global warming potential to reduce the complexity associated with the large number of individual emissions. Indices used to measure the impacts from use, maintenance and disposal of a building, as well as forest biodiversity and the carbon stored in the forest are developed separately since these effects occur over a long period of time in contrast to the narrow time frame associated with impacts from extraction to construction. Table ES-1 presents the indexes associated with production stages. ***With two exceptions, all of the construction index measures indicate significantly lower environmental risk for the wood framing design in Atlanta and Minneapolis compared to non-wood framing alternatives.*** The exceptions are that the steel design in Minneapolis produces less solid waste than the wood design although the difference is insignificant and there is no significant difference in the water pollution index for the Atlanta designs.

**Table ES.1. Environmental Performance Indices for Residential Construction.**

<b>Minneapolis design</b>	<b>Wood</b>	<b>Steel</b>	<b>Difference</b>	<b>Other Design vs. Wood (% Change)</b>
Embodied Energy (GJ)	651	764	113	17%
Global Warming Potential (CO <sub>2</sub> kg)	37,047	46,826	9,779	26%
Air Emission Index (index scale)	8,566	9,729	1,163	14%
Water Emission Index (index scale)	17	70	53	312%
Solid Waste (total kg)	13,766	13,641	-125	-0.9%
<b>Atlanta design</b>	<b>Wood</b>	<b>Concrete</b>	<b>Difference</b>	<b>Other design vs. wood (% change)</b>
Embodied Energy (GJ)	398	461	63	16%
Global Warming Potential (CO <sub>2</sub> kg)	21,367	28,004	6,637	31%
Air Emission Index (index scale)	4,893	6,007	1,114	23%
Water Emission Index (index scale)	7	7	0	0%
Solid Waste (total kg)	7,442	11,269	3,827	51%

The primary difference in materials between the Minneapolis wood and steel house is the substitution of 6,000 kg of steel for wood in the floors and walls. Both designs share the same basement and roof elements with the total weight of all structural materials approaching 100,000 kg. The substitution of 6% of the materials by weight results in a substantial percentage increase in all of the environmental performance indices except solid waste, which is essentially unchanged.

For the Atlanta structure, the major difference between the wood and concrete design is the substitution of 8,000 kg of concrete (2,000 kg of limestone plus rebar and aggregate material) for 2,000 kg of wood in the exterior wall structure as both designs use similar concrete floors and wood roofs. The substitution of 8% of the materials by weight results in a substantial percentage increase in all of the environmental performance indices except water, which is essentially unchanged.

It is instructive to compare subassemblies given the many common components in the residential construction. Tables ES-2 and ES-3 present the environmental indexes for the above-grade wall, and floor and roof assemblies respectively. Across designs, the comparisons for the wall and floor sections generally show larger percentage differences than for the buildings as a whole since the materials being substituted make up a larger share of the subassemblies.

**Table ES.2. Environmental Performance Indices for Above Grade Wall Designs.**

<b>Minneapolis design</b>	<b>Wood</b>	<b>Steel</b>	<b>Difference</b>	<b>Other Design vs. Wood (% Change)</b>
Embodied Energy (GJ)	250	296	46	18%
Global Warming Potential (CO <sub>2</sub> kg)	13,009	17,262	4,253	33%
Air Emission Index (index scale)	3,820	4,222	402	11%
Water Emission Index (index scale)	3	29	26	867%
Solid Waste (total kg)	3,496	3,181	-315	-9%

<b>Atlanta design</b>	<b>Wood</b>	<b>Concrete</b>	<b>Difference</b>	<b>Other design vs. wood (% change)</b>
Embodied Energy (GJ)	168	231	63	38%
Global Warming Potential (CO <sub>2</sub> kg)	8,345	14,982	6,637	80%
Air Emission Index (index scale)	2,313	3,373	1,060	46%
Water Emission Index (index scale)	2	2	0	0%
Solid Waste (total kg)	2,325	6,152	3,827	164%

**Table ES.3. Environmental Performance Indices for Floor & Roof Assemblies.**

<b>Minneapolis design</b>	<b>Wood</b>	<b>Steel</b>	<b>Difference</b>	<b>Other Design vs. Wood (% Change)</b>
Embodied Energy (GJ)	109	182	73	67%
Global Warming Potential (CO <sub>2</sub> kg)	3,763	9,650	5,914	157%
Air Emission Index (index scale)	981	1,813	832	85%
Water Emission Index (index scale)	17	70	53	312%
Solid Waste (total kg)	13,766	13,641	-125	-0.9%

The Minneapolis wood wall subassembly uses less energy, and produces less GWP than the steel wall subassembly that incorporates an outside layer of insulation to provide equivalent thermal properties. The steel disadvantage is substantially greater in the floor where stiffness becomes more important. The Atlanta wall concrete subassembly comparison is substantially worse given little savings in the wood used in the concrete house as a wood frame is still used inside the concrete to house the insulation and its gypsum covering.

In effect a substantial environmental performance difference for nearly substitutable products may not seem so great for a completed structure with many common components but can be much more significant for subassemblies. The large percentage of common components of wood, concrete and steel in all designs suggests that the materials are more often complements than substitutes. The noted differences between the wood and steel wall versus the wood and steel floor also suggest that the design itself, based on the intrinsic properties of the materials, can have a substantial impact.

From experience with sensitivity analysis ATHENA™ considers relative differences of less than 10-15% as not significantly different. However when differences are developed at the subassembly level like walls or floors which individually may make up less than one-third of the total, smaller differences may be significant, especially since a larger portion of the data was derived from primary surveys at the plant level. In particular, the wood product data is based on primary surveys of mills, where the mass balances between inputs and outputs was generally within 1 - 2%, hence it is believed that the wood measurements should be within 5%. Similarly more of the other products used in the subassemblies are based on primary data raising the quality of the data for these comparisons.

## **IMPACTS OF WITHIN WOOD SUBSTITUTION**

Within wood substitution was also analyzed. The substitution of plywood for OSB, simulating the practice of a few years back, generally resulted in 3% lower environmental burdens for the completed house except for water which may simply reflect a more complete response by OSB mills to changing compliance standards regarding water emissions. The substitution of solid-sawn wood joists for engineered I-joists shows very little difference between the environmental performance indices as the increased use of resins and energy is offset by the greater material efficiency of the I-joists. The use of green Douglas-fir lumber for studs, which is still prevalent in the west, reduces energy by 4% and GWP by 2%. Other low-grade co-products could be used as biofuel, lowering the energy requirement and especially for drying. Sensitivity analysis revealed that using all co-product material except chips for paper production as biofuel generally results in surplus energy for the production of all wood products except OSB, offsetting some of the energy purchased for the production of steel, concrete, insulation, and other materials.

These substitutions also raise issues on material-use efficiency. OSB is produced from wood of several species, generally considered of lower value. In that sense OSB reduces the pressure on the acres that have been producing higher quality wood and are in greater demand. This results in a substantial productivity increase in terms of total production per acre of forestland. In addition, the I-joists use OSB and require less wood per house. I-joists use only 62-65% of the wood required by solid-sawn joists. Since I-joists were only used in the floor in designs studied, returning to the use of solid sawn joists would increase the use of wood fiber by 10% (1.3 tonnes) for the total house and this wood would generally be higher valued species i.e. in greater demand. These material use efficiency gains are quite significant when wood used is traced back to the producing land base.

## ENERGY USE FROM CRADLE TO GRAVE

Modules J-M describe the energy used in representative residential buildings across their life cycle. The energy used to produce the construction materials and build the house are provided in module J, heating and cooling energy over the life of the building in module K, energy for maintenance in module L, and the energy used in demolition in module M. Table ES-4 summarizes the energy used for each life cycle stage. The energy used in heating and cooling dominates the energy used in all other stages of the life cycle. However from an economic standpoint, since the energy used in heating and cooling is spread over the 75-year life cycle, the present value cost is a relatively small share of the total investment in construction.

Since there is an insignificant difference in the energy used for heating and cooling between different framing methods and these differences could be reduced to zero by small design changes such as the use of insulation, the table adopts the energy use for heating and cooling for the wood framing unit as the standard. By far the largest maintenance requirement is the roof, which was common for all framing designs studied, so again only the maintenance for the wood framing design is shown. For demolition there is a slightly higher use of energy for the heavier and bulkier concrete structure.

The energy in the structure is derived from CORRIM's primary mill surveys customized to the bill of materials in the representative house designs. Energy use over the life of the house is derived from Department of Energy sponsored models for which the customization to our representative houses is much less exacting although believed to be sufficient to make relative comparisons to the energy in the structure. Energy for maintenance was based on housing surveys that could not be customized to our specific housing designs. While the accuracy of the energy used in the use, maintenance and disposal stages is inherently lower, the estimates do serve to place the relative levels of energy use into perspective. The CORRIM focus has been on the energy in products and structures, which are believed to be very reliable.

**Table ES.4. Energy used in representative building life cycle stages**

	Minneapolis House		Atlanta House	
	Wood Frame	Steel Frame	Wood Frame	Concrete Frame
Energy in the Structure (GJ)	646	759	395	456
Energy from Maintenance (GJ)	73	73	110	110
Energy for Demolition (GJ)	7	7	7	9
<b>Energy Subtotal</b>	<b>727</b>	<b>840</b>	<b>512</b>	<b>573</b>
<i>House Cost</i>	<i>\$168,000</i>	<i>\$168,000</i>	<i>\$135,000</i>	<i>\$135,000</i>
<i>Construction Cost</i>	<i>\$92,000</i>	<i>\$92,000</i>	<i>\$74,000</i>	<i>\$74,000</i>
<b>Energy Use heat &amp; cool (GJ) (75 yrs)</b>	<b>7800</b>	<b>7800</b>	<b>4575</b>	<b>4575</b>
<i>Cost/yr heat &amp; cool</i>	<i>\$692</i>	<i>\$692</i>	<i>\$491</i>	<i>\$491</i>
<i>Present Value Cost (75-years @ 5%)</i>	<i>\$13,490</i>	<i>\$13,490</i>	<i>\$9565</i>	<i>\$9565</i>
<b>% of Construction \$</b>	<b>14.7</b>	<b>14.7</b>	<b>12.9</b>	<b>12.9</b>

While the energy use for heating and cooling is roughly ten times the energy used in construction, maintenance and demolition, the cost is less than 1/7th the cost of construction. Reducing energy use to zero, a goal of the Department of Energy, may be difficult but one could spend an additional \$13,490 on the Minneapolis house or \$9,565 on the Atlanta house to reach that objective at an interest cost of 5% (adjusted for inflation). Reducing the energy in construction is sensitive to the design of the building and the processing efficiency of materials with the use of wood materials substantially more efficient than fossil intensive substitutes like steel and concrete.

While the total embodied energy in the steel frame house was 759 GJ compared to 646 GJ for the wood frame house the contribution of wood products to this number is very small. When we look only at the steel, wood and insulation being substituted the energy for these products less bio-energy, which is internally generated and renewable, are: 164 GJ for the steel frame (22% of the total) and 43 GJ for the wood frame (7% of the total). The explanation for this much reduced energy consumption is the high energy intensity of the products other than wood, steel and insulation that is common to both houses such as concrete, glass, gypsum and asphalt roofing. ***While the total energy in the steel house is only 17% greater than the wood house, for the products being substituted the steel frame uses 281% more non-bio energy than the wood frame.*** The substitution of steel and insulation for wood increases the non bio-energy in steel and insulation by 127 GJ with only a 7 GJ decrease in the energy to produce the wood. While the steel frame uses much more energy than the wood frame, the energy used by products other than steel and wood that are common to both designs is substantially greater.

Similar comparisons for the concrete house show 461 GJ embodied energy compared to 398 GJ for the wood house. Looking only at the concrete and rebar which substitutes for wood in the concrete house the energy uses less bio-energy are: 84 GJ for the concrete frame (18% of the total) and 24 GJ for the wood frame (6% of the total). ***While the total energy in the concrete frame is only 16% greater than the wood house, for the products being substituted the concrete frame uses 250% more non-bio energy than the wood frame.*** The substitution of concrete block, mortar and rebar requires 63 GJ more energy while the wood energy use decreases by only 3 GJ. Similar to the steel comparison, the concrete frame uses much more energy than the wood frame but the energy in products common to both designs including the concrete floor and foundation are substantially greater.

## **CARBON EMISSIONS FROM CRADLE TO GRAVE**

The carbon emissions associated with energy use represent one of the more important environmental burdens but in this case the carbon in the forest provides an offset to the emissions from construction and building use. Table ES.5 accumulates the carbon emissions (and avoided emissions) associated with the life cycle of a house.

**Table ES 5. Carbon emissions in representative building life cycle stages**

CO <sub>2</sub> Tonnes	Minneapolis House		Atlanta House	
	Wood Frame	Steel Frame	Wood Frame	Concrete Frame
Emissions in Mfg Construction & Demo	37.1	46.8	21.4	28.0
Emissions from Biofuel	3.6	2.6	3.4	2.7
Emissions from Maintenance	3.4	3.4	4.1	4.1
Emissions from Heating & Cooling	390	390	232	232
<b><i>Subtotal of Sources</i></b>	<b><i>434</i></b>	<b><i>443</i></b>	<b><i>261</i></b>	<b><i>267</i></b>
Forest Sequestration	(467)	(246)	(103)	(85)
Wood product Storage	(22.4)	(11.8)	(17.1)	(14.1)
<b><i>Subtotal of Sinks and Stores</i></b>	<b><i>(489)</i></b>	<b><i>(258)</i></b>	<b><i>(121)</i></b>	<b><i>(100)</i></b>
<b>Net emissions</b>	<b>(55)</b>	<b>185</b>	<b>140</b>	<b>167</b>

Emissions, from harvesting, product manufacturing, construction and demolition are added to the emissions from maintenance, heating and cooling for a subtotal of emission sources. But to a large degree the level of carbon dioxide from these emissions are offset by that removed from the atmosphere through the growth of trees and stored in forests and products.

While the total sources of emissions are dominated by the impact of energy used in heating and cooling, the forest and wood product sinks for carbon tend to be larger for the Minneapolis wood frame house. The net CO<sub>2</sub> avoided is 55 tonnes for the Minneapolis wood frame house, compared to a net source of emissions of 185 tonnes for the steel frame, 140 for the Atlanta wood frame, and 167 for the concrete frame, i.e., only the Minneapolis wood frame shows more carbon stored than emissions. The shorter rotation in the southeast sequesters less carbon in the forest. We do not account for the slow and partial decomposition of the carbon stored in products after demolition since they occur well outside of the useful life stage of the house. We only show the carbon in the forest that is allocated to products used for the house. If the waste wood products from home demolition were burned for energy value the displacement of fossil energy sources should be larger than the emission from burning. However if landfilled, which remains the dominant disposal method in the US, that portion that decomposes would reduce the carbon stored in products. The relative rankings of total storage are not altered by including these models of end of life decomposition. Any decomposition occurs beyond the time period for the useful life of the house. Future research is needed to better characterize the impact of final product disposal while noting that these processes will likely change substantially over time.

Integration over all of the activities performed on today's stocks of forest lands and housing, coupled with today's processing, construction, and demolition and disposal methods, provides a realistic "bottom line" inventory report on the current status of resource and energy consumption and releases to the environment. However efforts to identify cost effective improvements may need to take into consideration the time value of money which differs across several of these life cycle stages.

An alternate perspective more related to forest management tracks the carbon over time, in the forest, in both short- and long-lived products, in biofuel displacement of fossil energy, and product substitution. Unlike the above lifecycle analysis, which assumes stability over time, the time series analysis developed in module N shows the dynamic impacts of carbon flowing from a managed acre. While the carbon stored in the forest approaches long term stability, the carbon available for products continues to grow either supporting an increase in housing units or carbon displacement from the substitution of wood for fossil intensive products. The displacement of fossil intensive products is a very important factor in full carbon accounting.

## **ENVIRONMENTAL IMPROVEMENT OPPORTUNITIES**

The report identifies many areas where environmental improvement opportunities would appear to be attractive and benefit from further work.

- Redesign of the house to use less fossil intensive products
- Redesign of the house to reduce energy use (both active and passive)
- Revising building codes to reduce excessive use of products
- Greater use of low valued wood fiber for biofuel
- Greater use of engineered products producing higher valued products from less desirable species while also using less material per unit of construction
- Improved process efficiencies such as the boiler or dryer (including air drying)
- Environmental pollution control improvements evaluated using LCI/LCA
- More intensive forest management
- Recycling demolition wastes
- Increased product durability (given the already long expected life of a house, from 75-100 years, this applies primarily to moisture/weather exposed areas)



# LIFE CYCLE ENVIRONMENTAL PERFORMANCE OF RENEWABLE MATERIALS IN THE CONTEXT OF RESIDENTIAL BUILDING CONSTRUCTION

Consortium for Research on Renewable  
Industrial Materials

October 28, 2004  
Revised July 20, 2004

## Phase I Research Report

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- Module B: Softwood Lumber – Pacific Northwest Region
- Module C: Softwood Lumber – Southeast Region
- Module D: Softwood Plywood Manufacturing – Pacific Northwest and Southeast
- Module E: Southeastern Oriented Strandboard
- Module F: Composite I-joists – Pacific Northwest and Southeast
- Module G: Glue-laminated Beams – Pacific Northwest and Southeast
- Module H: Laminated Veneer Lumber – Pacific Northwest and Southeast
- Module I: Design of Residential Building Shells – Minneapolis and Minnesota
- Module J: Environmental Impacts of a Single Family Building Shell – From Harvest to Construction
- Modules K,L,M Integrated:
- K: Energy Consumption and Associated Greenhouse Gas Emissions Related to Heating, Cooling and Occupying Virtual CORRIM Houses in Atlanta and Minneapolis
- L: Energy Consumption and Associated Greenhouse Gas Emissions Related to Maintenance of a Residential Structure
- M: Energy Consumption and Associated Greenhouse Gas Emissions Related to Deconstruction and Demolition of a Residential Structure
- Module N: Carbon Tracking from Sequestration in the Forest to Wood Products and Substitution
- Module O: Environmental Performance Index for the Forest

## 1.0 INTRODUCTION

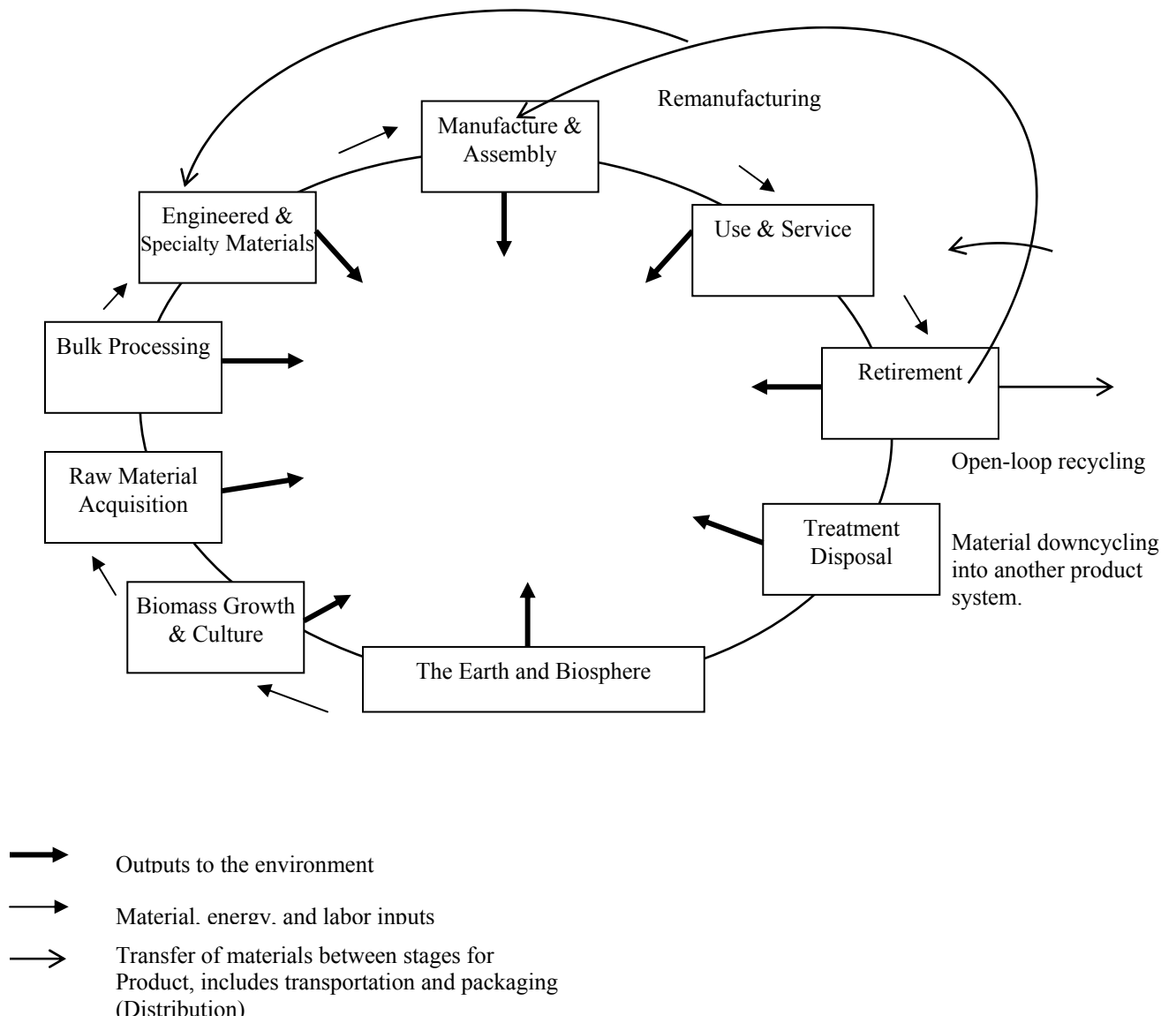
### 1.1 BACKGROUND

The motivation for creating CORRIM originates from the increasingly intense public interest and debate regarding environmental impacts and sustainability of building products manufacture and use, and, in particular, the intense concerns about forest management and the flows of products that originate from forests. Unfortunately, the environmental consequences of changes in forest management, product manufacturing, consumption, and disposal are poorly understood. There is a lack of current, scientifically-sound, Life Cycle data in the United States for wood and other bio-based products. CORRIM is the response to this lack of data and analysis.

The last major research effort in the United States dealing with these issues for wood and bio-based products was completed in 1976 by the Committee on Renewable Resources for Industrial Materials (CORRIM) under the auspices of the National Research Council (1976). Though a landmark study, information developed under CORRIM, referred to as CORRIM I, is now incomplete and out-of-date in the context of current issues and concerns.

Recognizing the need for updated and more comprehensive information the Consortium for Research on Renewable Industrial Materials (referred to as CORRIM II) was established to develop a scientific database of environmental performance measures of wood building products, and to examine factors that can affect the efficient use of energy and materials in manufacturing and using building materials. These factors include forest management that increases carbon sequestration, the efficiency of manufacturing processes, reduced waste and potentially toxic materials, and sustaining healthy forest ecosystems. The intent in establishing CORRIM II was to develop:

- A consistent database to evaluate the environmental performance of wood and alternative materials from resource regeneration or extraction to end use and disposal, i.e. from “cradle to grave” (Figure 1.1).
- A framework for evaluating Life Cycle environmental and economic impacts.
- Source data for many users, including resource managers, manufacturers, architects, engineers, environmental protection and energy analysts, and policy specialists.
- An organizational framework to obtain the best science and peer review.



*Source:* Adapted from Leoleian and Menerey 1993

**Figure 1.1. Integrated Life cycle of Biological Materials**  
*Source:* (CORRIM 1998)

CORRIM II is a non-profit corporation of scientists from member research organizations (Table 1.1).

**Table 1.1. The Research Organizations Comprising CORRIM II**

---

• APA—The Engineered Wood Association	• University of Idaho
• Athena Sustainable Materials Institute (Cooperator)	• University of Minnesota
• Composite Panel Association	• University of Tennessee (Currently inactive)
• FORINTEK Canada Corp.	• University of Washington
• Louisiana State University	• USDA-Forest Service, Forest Products Laboratory (Advisory)
• Mississippi State University (Currently inactive)	• Virginia Tech University
• North Carolina State University	• Washington State University (Currently inactive)
• Oregon State University	• Western Wood Products Association
• Purdue University	

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In 1994 CORRIM II responded to a request for proposals made by the American Forest and Paper Association (AF&PA) as part of its Agenda 2020 program. The Agenda 2020 program focuses on pre-competitive research needs of the US forest products industry, and the 1994 request targeted two principal research objectives relative to environmental life cycle inventory and analysis: (1) an updated analysis of the environmental efficacy of renewable building materials, including consideration of environmental impacts related to energy consumption, and (2) the identification of alternatives for reducing environmental releases associated with building materials through their Life Cycles. In 1996, the US Department of Energy and the forest products industry funded CORRIM II to develop a research plan. The research plan released in January 1998 outlined activity for 22 modules over a 5-year span (Table 1.2), (CORRIM 1998). Protocols and standards were described in the research plan to ensure that data collection, analysis, reporting and review would be compatible with ISO Life Cycle analysis guidelines (ISO 1997, 1998, 2000a, 2000b) and life cycle inventory (LCI) procedures developed for the forest industry (AF&PA 1996).

**Table 1.2. CORRIM II Research Modules – (from CORRIM 1998)  
Phase I Research consists of Highlighted Areas**

All estimated funding (monetary figures) are in \$ 000's

FOCUS AREA	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Forest Resource	1. Forest Resource I Regional – NW/SE \$400		13. Forest Resources II Regional – NE/NC/IW/Canada \$400			
Manufacturing Processes	2. Processes I Structural Products \$400		14. Processes II Nonstructural Products \$600			
Structures	3. Structures Ia Component Systems \$200		5. Structures Ib Complete Structures \$200		16. Structures II Alternatives \$200	
Data Management	4. Data Management (Funded as part of each module)					
Industrial Products		6. Industrial Products Treated/Untreated \$150			20 Structures III Infrastructures \$150	
Integrated Modeling		7. Integrated Modeling \$200		17 & 21. Integrated Modeling II a&b \$300		
Nonstructural Products		8. Nonstructural Products I Windows/doors/insulation etc.			18. Nonstructural Products II Millwork, flooring, etc. \$200	
Products Substitution		9. Substitution I Components \$200		15. Substitution IIa Comprehensive Structure \$200		19. Substitution IIb Nonstructural \$100
Biomass	10. Biomass Process for Energy \$200					
Use, Disposal, Life Expectancy, Durability		11. Life Expectance/Durability \$150		12. Use/Maintenance/Disposal/ Final Recycle \$300		
Reporting		22. Reporting/Technology Transfer \$250				
Total Funding Need						
	\$5000					

The initial budget proposal (highlighted in Table 1.2) of \$1.5 million for the 5 modules making up the Phase I Research Plan was pared down to \$600,000 cash support and more than \$300,000 institutional matching support as funding sources became constrained. Projects were reduced in scope, especially the Use/Maintenance/Disposal/Final Recycle module, and unfunded institutional match time increased by default.

Preceding the CORRIM II initiative was a project to develop current environmental performance information for building materials used in Canada. This project, titled “Building Materials in the Context of Sustainable Development”, was initiated in 1990 as the ATHENA™ project by FORINTEK Canada Corp, and is now continuing at the Athena Sustainable Materials Institute. In 1997, an alliance was established between CORRIM and ATHENA™ to take advantage of previous ATHENA™ research and to broaden the geographic and product representation of research.

## 1.2 OBJECTIVES, MODULAR DESIGN, AND SCOPE OF CORRIM PHASE I

Funding<sup>3</sup> to conduct a first phase effort (modules 1-4, 7, and a portion of 12 as highlighted portions of Table 1.1) was made available to pilot test the procedures that would be needed for the ultimate development of the full 22-module CORRIM II research plan. The Phase I effort has two objectives:

- to develop an adequate database and models of environmental performance measures over the entire Life Cycles of structural building materials, beginning with extraction of resources, through product manufacture and transportation, construction of a structure, use and maintenance of the structure, and finally dismantling of the structure and either disposal or recycling of the building components; and
- to examine a range of management, product, and process alternatives to identify strategies that can improve the environmental performance of sustainable building materials.

The Phase I research effort concentrated on the development of LCI data for wood-based building materials produced in the two regions of the US that account for the greatest production of forest products – the Pacific Northwest and the Southeast. Further, because of funding limitations, the scope of Phase I was limited to consideration of the structural shells or envelopes of residential buildings excluding internal and non-structural materials such as trim, cabinets, lighting, heating, and appliances. Although focused on wood-based materials, Phase I research did address environmental performance of wood-framed buildings in comparison to residential buildings framed with steel and concrete block.

To a very large degree, wood, steel and concrete are used in every building with each being used where they hold some economic and or structural performance advantage. Each can be used as the primary framing method and wood frame structures are dominant with 86% of the market followed by concrete with 9% and steel with 2% including both single- and multi-family wall systems (APA 2002). The concrete share is higher in the Southeast and Southwest although still substantially behind the share for wood frame. As noted in module J, these three materials are each used in every house with the method of framing determining which makes up the largest share. Even when the primary material used for framing is changed, it represents a rather small change to the overall bill of materials in the house, as low as 6% on a weight basis. In that sense the materials appear to be more complimentary than competitive. LCI Data for the non-wood materials was obtained from the Athena Sustainable Materials Institute.

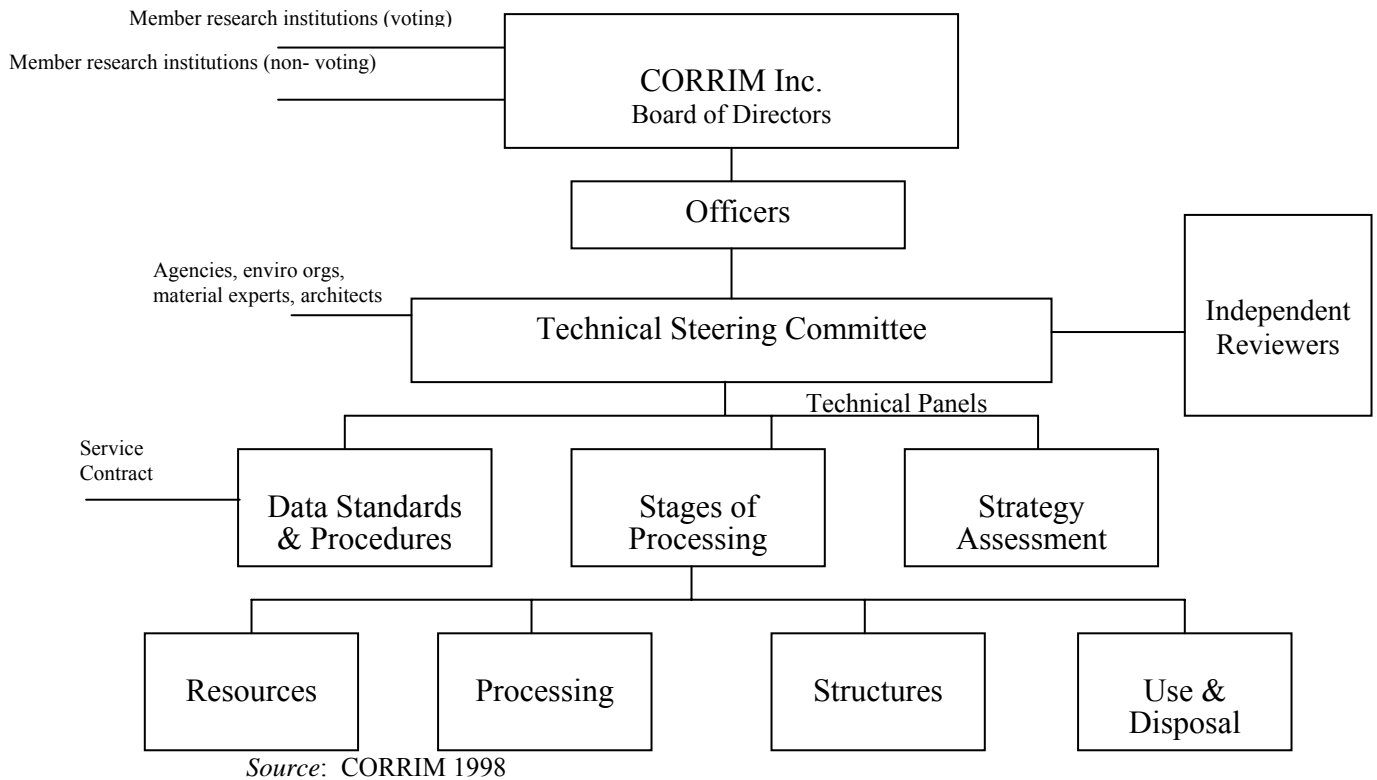
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<sup>3</sup> Phase I funding sources included contributions from USFS FPL, Weyerhaeuser, Simpson, Longview Fiber, Georgia Pacific, Louisiana Pacific, Temple Inland, Potlatch, International Paper, Champion, in cooperation with matching funds from University of Washington, University of Minnesota, Oregon State University, Virginia Tech University, North Carolina State University, Mississippi State University, and University of Idaho.

### 1.3 ORGANIZATIONAL FRAMEWORK TO CONDUCT PHASE I RESEARCH

An organizational structure has been established for CORRIM II to provide the best scientific talent available to complete the research while obtaining competent and independent reviews. This structure is organized around working panels of experts (Figure 1.2) including a Data Standards and Procedures Panel, a Stages of Processing Panel (with 4 technical sub-committees), and a Strategy Assessment Panel.

**Figure 1.2. CORRIM Organization Chart**



The Data Standards and Procedures Panel has responsibility for providing data processing capability, assuring consistency and compatibility in the design of data collection procedures across research modules, and integrating the results of management and technology alternatives throughout all stages of processing. Development of LCI data, on the basis of individual unit operations, for a range of wood-based building materials from harvesting and forest regeneration through manufacturing, transport, construction of residential structures, building maintenance, and reuse or disposal at the end of the useful life of the building or building component is the responsibility of the Stages of Processing Panel. The Strategy Assessment Panel is charged with development and evaluation of a number of scenarios that represent various strategies for improving environmental performance of wood-based building materials throughout their life cycles.

The specific assignment of scientists from CORRIM member institutions to the Phase I modules is presented in Table 1.3.

**Table 1.3. Lead Scientists Involved in CORRIM - Phase I Chair of Technical Steering Committee, Dr. Jim Bowyer, University of Minnesota**

<b>Contribution</b>	<b>Principal Investigator</b>	<b>Member Institution</b>
<b>Stages of Processing Modules</b>	Dr. Jim Wilson	Oregon State University
<b>Forest Resources Modules</b>		
Forest Resources I	Dr. Leonard Johnson	University of Idaho
Carbon Sequestration	Dr. John Perez-Garcia	University of Washington
Forest Environmental Performance	Bruce Lippke	University of Washington
<b>Processes Modules</b>		
Softwood lumber-Pacific NW	Dr. Mike Milota	Oregon State University
Softwood lumber-SE	Dr. Mike Milota	Oregon State University
	Dr. Cynthia West	Mississippi State University
Plywood	Dr. Jim Wilson	Oregon State University
Oriented strandboard	Dr. Earl Kline	Virginia Tech University
I-joists & beams	Dr. Jim Wilson	Oregon State University
Glued laminated beams	Dr. Jim Wilson	Oregon State University
Laminated veneer lumber	Dr. Jim Wilson	Oregon State University
<b>Structures Module</b>	Dr. Bo Kasal	North Carolina State University
<b>Use, Maintenance and Disposal Modules</b>		
	Dr. Paul Winistorfer	Virginia Tech University
<b>Life Cycle Inventory through Construction</b>		
	Dr. Jamie Meil	Athena Sustainable Materials Institute
<b>Data Management &amp; Integration</b>	Dr. David Briggs	University of Washington
	Bruce Lippke	University of Washington
	Dr. Jim Bowyer	University of Minnesota

## 1.4 REPORT STRUCTURE

This final report updates an interim report that was published in March 2002. The interim report described progress through the first half of the Phase 1 research activity. The intent of the interim report was to develop procedures and collect data while identifying and correcting deficiencies before completion of the final Phase I research report. The mid-term comprehensive review led to a number of improvements, in both the primary source data and secondary ATHENA™ data. The final Phase I report contains additional sensitivity and scenario analyses on the impact of management and technology change as a result of mid-term findings.

This report is designed around individual research modules comprising Phase I of the project. These modules are in effect stand-alone reports covering each stage of processing through construction, use, maintenance and disposal of a residential building structure. LCI data is provided for each wood product used in the structure and construction of the building and an index for forest ecology for which there is no counterpart for non-renewables. The modules are:

- **Module A: Forest Resources - Pacific Northwest and Southeast** – identifies environmental performance measures and presents life cycle inventory data for specific unit operations in woodland management activities in forests of the Pacific Northwest and Southeast regions.

The objectives of this module are to:

- Provide environmental, energy, and resource impact data on the growth, management, harvesting and reforestation of timber for a range of management intensity scenarios for the Northwest and Southeast regions of the United States.
  - Develop case studies to represent a typical range of forest management objectives and stand and site conditions.
  - Provide economic data for the case studies that can be used in environmental improvement analysis.
  - Provide environmental performance measures including carbon and indices of stand structure diversity, as the primary change agent affecting habitat for each of the case study scenarios.
  - Provide inputs for the Processing Modules from the case study scenarios.
- **Module B: Softwood Lumber - Pacific Northwest Region** – presents life cycle inventory data for specific unit operations associated with the manufacture of softwood lumber in the Pacific Northwest region of the United States.

The objectives of this module, as well as modules C-H (other softwood products and regions) are to:

- Provide environmental, energy, and resource impact data on the manufacture of a specific product in a specific supply region.
- Provide benchmarks for these products that will enable comparison to process improvements or new processes.
- Provide economic benchmark data that can be used in environmental improvement analysis.
- Provide input for the Structures Module.
- Provide an accounting of carbon and compare fossil versus biomass fuel dependency.
- Provide a measure of resource use efficiency.

- **Module C: Softwood Lumber – Southeast Region** – presents life cycle inventory data for specific unit operations associated with the manufacture of softwood lumber in the Southeast region of the United States.
- **Module D: Softwood Plywood Manufacturing – Pacific Northwest and Southeast** - presents life cycle inventory data for specific unit operations associated with the manufacture of softwood plywood in the Pacific Northwest and Southeast regions of the United States.
- **Module E: Southeastern Oriented Strandboard Production** – presents life cycle inventory data for specific unit operations associated with the manufacture of oriented strandboard in the Southeast region of the United States.
- **Module F: Composite I-joists – Pacific Northwest and Southeast** – presents life cycle inventory data for specific unit operations associated with the manufacture of I-joists from lumber in two specific regions, the Pacific Northwest and the Southeast.
- **Module G: Glue-laminated Beams – Pacific Northwest and Southeast** – presents life cycle inventory data for specific unit operations associated with the manufacture of glulam beams from lumber in two specific regions, the Pacific Northwest and the Southeast.
- **Module H: Laminated Veneer Lumber – Pacific Northwest and Southeast** – presents life cycle inventory data for specific unit operations associated with the manufacture of laminate veneer lumber in two specific regions, the Pacific Northwest and the Southeast.
- **Module I: Design of Residential Building Shells - Minneapolis and Atlanta** – outlines the design of typical light-frame residential structures for two different climates: a hot and humid climate represented by Atlanta, GA, and a cold climate, represented by Minneapolis, MN, for use in subsequent life cycle analyses of representative structures.

The objective of this module is to:

- Develop the bill of materials consistent with best practices and building codes for a typical cold and warm climate. The bill of materials makes it possible to integrate across the LCI information for each product represented to develop the LCI for a residential structure.
- **Module J: Environmental Impacts of a Single Family Building Shell – From Harvest to Construction** – presents the results of a comprehensive analysis of environmental impacts related to the construction of wood and non-wood materials in residential structures.

Objectives of this module are to:

- Provide environmental, energy, and resource impact data on the manufacture of representative single residential structures, comprised of floor, wall and roof components (with considerations for windows, doors, roofing and siding based on ATHENA<sup>TM</sup> data).

- Provide environmental, energy, and resource impact data on the manufacture of a key wall section subassembly where the substitution between materials is more direct than the total house.
- Provide input for the Use and Disposal Module and future Structures Modules that will include internal components and fixtures.
- Provide data input for the integration of all stages of processing.
- Compare fossil versus biomass fuel dependency.
- Provide measures of resource use efficiency.
- **Module K: Energy Consumption and Associated Greenhouse Gas Emissions Related to Heating, Cooling and Occupying Virtual CORRIM Houses in Atlanta and Minneapolis** – provides information on total annual energy used by occupants for comparison to the energy used in construction.

The objectives of this module are to:

- Provide information on the use phase of residential structures as a supplement to the energy used in the construction of a building.
- Provide information on the energy use associated with the structure itself such as heating and cooling compared to the energy use associated with appliance use such as water heating, lighting, stoves etc.
- Compare the energy associated with the use of the building with the energy used in construction.
- **Module L: Energy Consumption and Associated Greenhouse Gas Emissions Related to Maintenance of a Single Family Residential Structure** – provides information on energy used to maintain single family residential structures.

The objectives of this module are to:

- Estimate the useful life of wood materials used in the structural shell of a building
- Provide information on the environmental performance measures resulting from the maintenance activities usually associated with the life cycle of the residential building shell.
- Provide input data for other modules that depend on the useful life of a building.
- **Module M: Energy Consumption and Associated Greenhouse Gas Emissions Related to Deconstruction and Demolition of a Residential Structure** – provides information on the final disposition of components upon dismantling of a building along with the associated impacts on life cycle inventories.

The objectives of this module are to:

- Estimate the environmental impacts of dismantling residential structures at the end of their useful life.

- Provide input data for other modules that depend on the useful life of a building.
- **Modules K, L, and M have been integrated into one summary report covering Use, Maintenance and Disposal**
- **Module N: Carbon Tracking from Sequestration in the Forest to Wood Products and Substitution** – provides information on carbon sequestration in forests, products and fossil fuel substitution.

The objectives of this module are to trace the impacts of forest management, processing of products, biomass conversion to energy and the substitution of non-wood materials on carbon sequestration.

- Provide information on the integrated impacts of forest management and residential construction on carbon pools.
  - Demonstrate the impact of different management alternatives (both short-term rotations with few investments in productivity enhancement, more intensive activities such as commercial thinning and fertilization, and longer rotations) on carbon through the life cycle of the forest through the product flows necessary for construction.
  - Maintain consistent boundary conditions in terms of residential units and acres employed to support those units.
- **Module O: Environmental Performance Index for the Forest** – provides information on how the ecology of the forest would be affected by different management alternatives.

The objectives of this module are to:

- Provide an index of forest diversity as a proxy for habitat for comparison with other environmental performance indices that derive from the use of renewable resources.
- Establish the baseline trend impacts of current management on forest structures that are key indicators for habitat suitability.
- Simulate the impacts of management alternatives for comparison with the baseline trend.

## 1.5 REPORT REVIEWS AND CONFORMITY WITH ISO 14'040 SERIES

The entire report was reviewed internally by many of the 23 authors of the report. Many sections of the report were made available to outside experts and their comments were incorporated. Critical external reviews were conducted of the LCI and LCA process for compliance with the assessments within the ISO 14'040s standards. The following are comments from the professional reviewers of the interim and final reports of this study.

The CORRIM Interim Phase I Report published in 2002 was professionally reviewed by Five Winds International, an experienced LCI/LCA consulting company. As a summary of their review:

*Our overarching comment is “congratulations” on developing a large, comprehensive and geographically-useful Life Cycle Inventory (LCI) database. Most of the critique we provide concerns clarity of presentation and consistency of reporting. It appears that the substance of work is quite solid and shall be useful to a wide body of stakeholders...*

Steven B. Young, PhD, PEng  
Director, Five Winds International  
199 Woolwich St., Guelph, Ontario, N1H 3V4, Canada

Their review also included many specific recommendations that set the stage for changes that were incorporated in this final report.

In January 2004 the final draft versions of the LCI Data Reports were professionally reviewed with an assessment of their compliance with the series of standards ISO 14'040ff relating to LCI/LCA by Dr. Frank Werner of Environment & Development, Zürich. He introduced his general comments with:

*First of all, I am really impressed by the extensive data collection this CORRIM Phase I has been able to generate! Believe me, I know how much work there is behind such a study!*

*But let me comment on the findings of my review. I have read the reports to check a) if they comply with the CORRIM research guidelines (Briggs 2000) and the ISO 14'040ff requirements, and b) if I was (virtually) able to transfer the reported data into another LCI software based on the description of the system and the data provided in the reports.*

*Most of the reviewed module reports only need minor modifications to be transparent and to comply with the ISO 14'040ff requirements.*

*Some points need special consideration and probably a decision of the CORRIM steering committee...*

Dr. Frank Werner  
Environment & Development  
Waffenplatzstrasse 89  
CH-8002 Zürich

CORRIM has responded diligently to the review comments for each module. A summary review text and a checklist for ISO compliance of the inventory modules A to M is provided in Appendix A to the main report.

Some recommendations did not receive a complete response and may be relevant to future research. We describe below our reasoning and note that given funding restrictions we are not convinced these are the highest research priorities.

- 1) Allocation of burdens based on mass, our most consistent metric, remains the standard for LCI/LCA work and was specified in our Research Guideline. The review recommendation to adopt a value allocation method has intuitive appeal but is both controversial and currently not practical. Our limited sensitivity analysis would not suggest it will significantly alter results and for such a large database project it is beyond our scope to provide a consistent methodology other than a mass allocation method. The determining factor for using mass allocation was that it is consistent with the secondary data for non-wood products that we access in the ATHENA™ EIE model. Even if we develop an alternative allocation system we would not have a consistent database available to compare with non-wood materials. There is a degree of truth that higher valued products will receive a higher allocated burden under a value-based allocation than under a mass allocation system. But the values cannot be measured at the unit process level requiring some additional arbitrary allocation system and they are not stable over time. As such they are more problematic than a well-quantified mass system and will result in less consistent methods used across a range of products. Our analysis of carbon under the assumption that all low-grade co-products are used as hog fuel provides an important sensitivity analysis as it represents a substantial reduction in the burdens assigned to co-products but did not reveal a magnitude of change that would alter conclusions. In fact by diverting co-products to energy production, wood products become energy self sufficient, substantially reducing emissions caused by the consumption of fossil fuels. Future research to evaluate the sensitivity of different allocation methods would be appropriate but is not a current high priority for CORRIM research. It will be considered if new products appear to be particularly sensitive to allocation methods. Our phase 2 research on MDF and Particleboard, both relying heavily on waste/coproducts, may increase the sensitivity of product burdens to allocation methods. It should be noted that the mass allocation system used in this study is performed at the unit process level, not at the mill level. Since the dominant source of burdens is generated from the use of energy which in turn is dominated by drying, most energy dependent burdens are allocated to the dried product with very little going to the coproducts generated by other unit processes. For most primary wood products, even though as much as 45% of the input mass may end up in coproducts, the dominant share of energy related burdens are allocated to products. Using those coproducts internally as a source of fuel reduces the energy related product burdens even further.
  
- 2) An assessment of data accuracy involving so many measurements is difficult. The range of variation in the primary survey data describes a range corresponding to an array of practices from something like best to worst except that our sample was not stratified to cover the full range of facilities. We can generally expect over time that the trend will favor investing in best practices. While we did obtain a large response to our survey, representing anywhere from 10 to 50% of total industry production for a given product and region, they were not randomly selected. However we took many steps to ensure that the data were accurate including having a project leader very familiar with their primary industry, conducting mass and energy balances of data, comparing data from plants within a region and between regions, and did follow up contacts to resolve outlier data. The range of data is not generally reported because it was not collected to be representative of all practices in the industry but is available in our SimaPro models.

- 3) It is very time consuming and costly to perform a comprehensive sensitivity analysis on the integrated results involving so many products and processes. We did do sensitivity analysis we thought critical such as changes in the use of co-products as hog fuel, forest management alternatives, drying etc. Future research to evaluate the sensitivities of integrated results to the range of variation in survey data would be appropriate but is not likely to alter conclusions and is therefore not a current high priority for CORRIM research.
- 4) It was recommended that we include the resource LCI in the product LCI, along with the transportation. Our analysis was designed to provide gate-to-gate analysis in modules. We roll up all the LCI data into a forest-to-building LCA report, which is reported in Module J. The rationale for this modularization was to provide the module results for inclusion in ATHENA™ EIE and the US LCI Database. In our Phase II effort we have given a high priority to developing cradle-to-gate product LCIs along with a table of add-on LCIs for transportation from the product-manufacturing gate to the building site. Product LCIs for the structural wood products that include resources are currently being added to the US LCI Database.
- 5) It was recommended that we include the energy content for wood materials. Again to be consistent with CORRIM protocol, ATHENA™ EIE, and the US LCI Database project we do not consider the feedstock energy of wood like we do for natural gas, crude oil, coal, and uranium. In the US, wood is not normally considered a fuel, and especially not when it is generated during demolition or recycling. Whereas, natural gas, crude oil, coal, and uranium are considered fuels, so their energy content is included. We clearly point out that the energy content of wood products is not considered except when used for hogfuel, an internal use.

A summary review text of the CORRIM phase 1 final report provided by Dr. Frank Werner is provided in Appendix A.

## **2.0 LIFE CYCLE ANALYSIS FRAMEWORK**

### **2.1 INTRODUCTION**

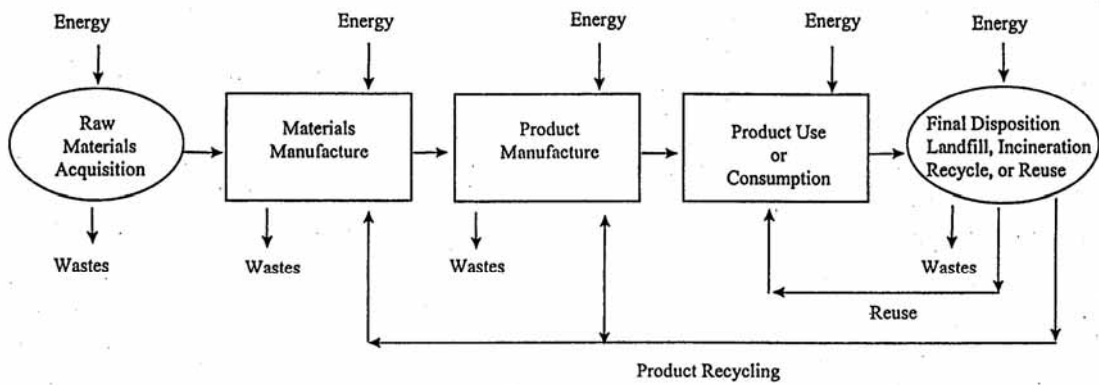
Life Cycle assessment (LCA), which began in the 1960s, has evolved as an internationally accepted way to address complex impact questions regarding the assessment of processes with complex inputs and outputs and their effects on the environment. “Life Cycle” refers to all activities from forest resource regeneration or mineral extraction through product manufacturing, to the end use of these products and their eventual disposal or recycle, i.e. from “cradle to grave” (Curran 1996). Guidelines to conduct LCAs are set forth in the ISO 14000 series of standards (ISO 1997, 1998, 2000a, 2000b). Counterpart national standards have been adopted in many countries and have been translated into guidelines for specific industries, an example of which is the AF&PA user’s guide for the US forest industry (AF&PA 1996).

### **2.2 CORRIM FRAMEWORK AND GUIDELINES**

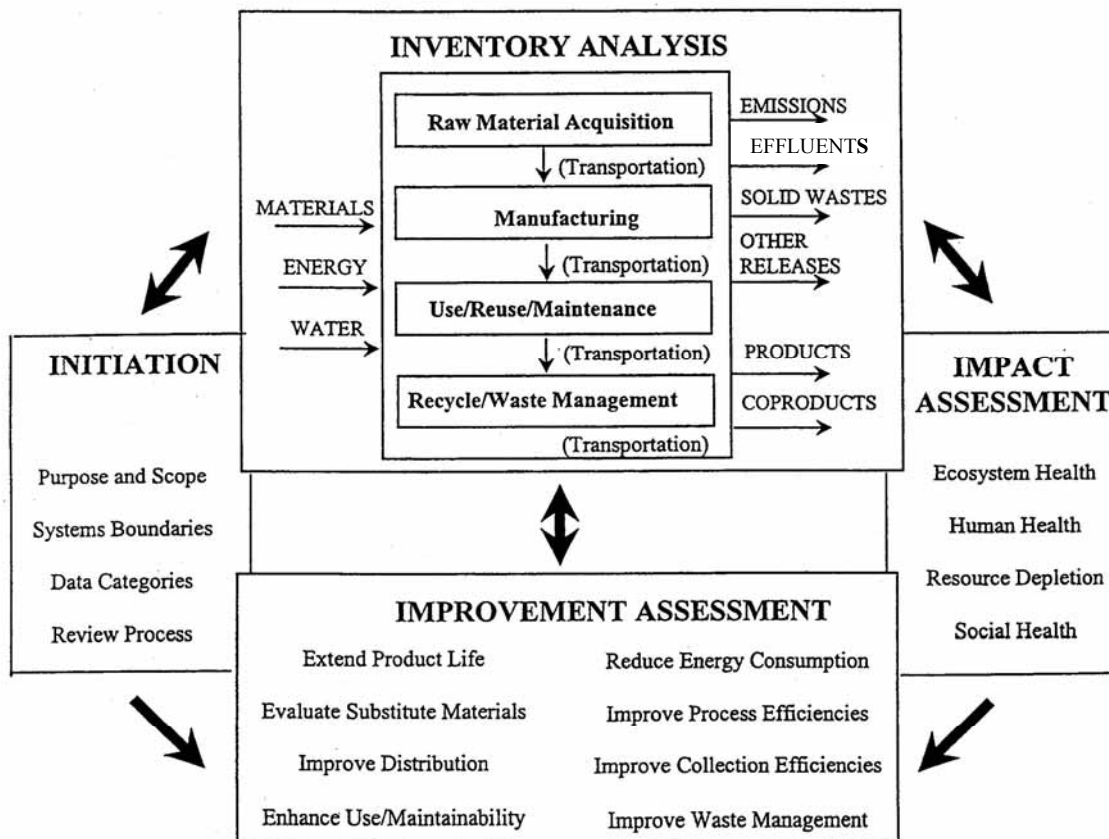
Figure 1.1 illustrates the overall approach employed by CORRIM to study biologically based materials, and identifies the linkages between the major steps in the life cycle of a building structure. Protocols and standards are described in the CORRIM research guidelines (CORRIM 2001) to ensure that data and analysis are consistent with methods for performing Life Cycle inventories and life cycle analyses as set forth in the ISO 14000 series of standards and AF&PA guidelines for the forest industry.

### **2.3 LIFE CYCLE ASSESSMENT (LCA)**

Figure 2.1 presents the general flows in a typical “cradle-to-grave” LCA and Figure 2.2 illustrates the major components of an LCA study. An LCA begins with an initiation phase during which a problem is defined along with the scope, system boundaries, data categories, and review process. Initiation is followed by three interrelated phases that may be conducted simultaneously or in a sequence that best suits the problem being studied: a life cycle inventory phase that identifies and quantifies the energy, resource use and environmental effects of a particular product, service, or activity; an impact assessment phase which investigates the potential environmental consequences of energy and natural resource consumption and waste releases associated with the system being studied; and an improvement assessment phase where opportunities to reduce environmental impacts and resource use are investigated. Figure 2.2 highlights some of the factors likely to be considered within each phase and emphasizes the iterative nature of the process.



**Figure 2.1. General Flows in a "Cradle-to-Grave" LCA System**  
 Source: Franklin Associates 1990



**Figure 2.2. Main Components of an LCA Study**  
 Source: ATHENA™ 1997a

## 2.4 Casting the CORRIM Framework in the LCA Context: Life Cycle Stages

The similarity between the CORRIM framework in Figure 1.1 and the generic Life Cycle approach presented in Figure 2.1 is evident. There are, however, two rather unique features of the CORRIM framework.

First, while some LCAs involving agricultural products or bio-energy have expanded the generic model by including a crop growing stage prior to raw material acquisition (Andersson & Ohlsson 1999, Mann & Spath 1997), forest growth is more complex. The relative complexity of forest growth is due to 1) the much longer time frame involved, 2) the use of intermediate harvests (thinning) to yield products, 3) the broader array of joint products arising from a single tree (saw, veneer, and pulp logs) and stand (due to mixed species having different use preferences), and 4) the unique set of forest co-products (water, recreation, berries and mushrooms, etc.) and environmental effects (such as water quality, species diversity, wildlife habitat, and carbon sequestration).

Second, buildings, which account for the largest use of wood in North America and the main focus of this study, are unique in their size, complexity, and longevity. For example, a residential home is constructed, used for a long period of time, and eventually demolished. The period of use and occupancy involves cycles of maintenance and repair (e.g. re-roofing) and may involve a series of owners each of which may remodel the structure to accommodate changes in desired functionality and aesthetics. As a result, the time frame between when tree seed germinates and when a home is demolished could be on the order of one to several centuries or more. Thus, the temporal distribution of events and associated environmental effects during the seed to demolition Life Cycle must be considered; merely summing all of the events and effects would produce the naïve and meaningless result that all of the activities and associated impacts occur simultaneously.

Table 2.1 highlights the major differences between the generic LCA model and the CORRIM framework. The major stages in the generic LCA model evolved for investigating consumer products and packaging materials with short lives where a simple temporal summation of effects is reasonable. Table 2.1 also indicates a rough estimate of time associated with each of the components of the CORRIM framework with comments identifying some of the associated activities and environmental effects. The procedure developed by CORRIM to deal with these temporal issues in LCA is discussed more fully in Section 2.6. Identification of these temporal aspects of the forestry and housing components leads to Figure 2.3, which shows the major stages in the cradle-to-grave cycle of a building such as a residential home and also illustrates the two long-term stages (forest growing and use of the building) that are important for carbon storage.

**Table 2.1. Comparison of the Generic LCA Model and the CORRIM Research Framework**

<b>Generic LCA Model</b>	<b>CORRIM</b>	<b>Comment</b>
	<u>Forest Growth</u> Time frame: 25-100 <sup>+</sup> years	Nursery, planting, thinning, fertilizing, during the growth cycle. Effects on carbon sequestration/global warming, diversity, habitat, streamside conditions, etc.
<u>Raw Material Acquisition</u>	<u>Harvesting</u> Time frame: < 1 year	Logging during commercial thinning or final harvest. Effects on soil compaction and productivity, diversity, habitat, siltation, etc.
<u>Manufacturing</u>	<u>Manufacturing Processes</u> Time frame: < 1 year	Individual products (lumber, plywood, LVL, OSB, etc) Assemblies of products (trusses, glulam beams, I-joists, etc.). Effects on air & water emissions, solid waste.
	<u>Construction of Structures</u> Time frame: < 1 year	On-site or factory built components (floor, wall, roof) and finished structure. Effects on solid waste.
<u>Use/Reuse/Maintenance</u>	<u>Service Life &amp; Use</u> Time frame: 40-100 + years House life: 75 + years	Maintenance cycles (painting, re-roofing, siding, etc.) and remodeling. Effects on energy use & associated emissions/waste, energy & emissions associated with repair/remodel products.
<u>Recycle/Waste Management</u>	<u>Recycling &amp; Disposal</u> Time frame: < 1 year	Teardown, segregation of materials, recycle, combust for energy, landfill. Effects on energy use & substitution, air & water emissions, solid waste/carbon sequestration.

## LIFE CYCLE ASSESSMENT OF WOOD BUILDING PRODUCTS

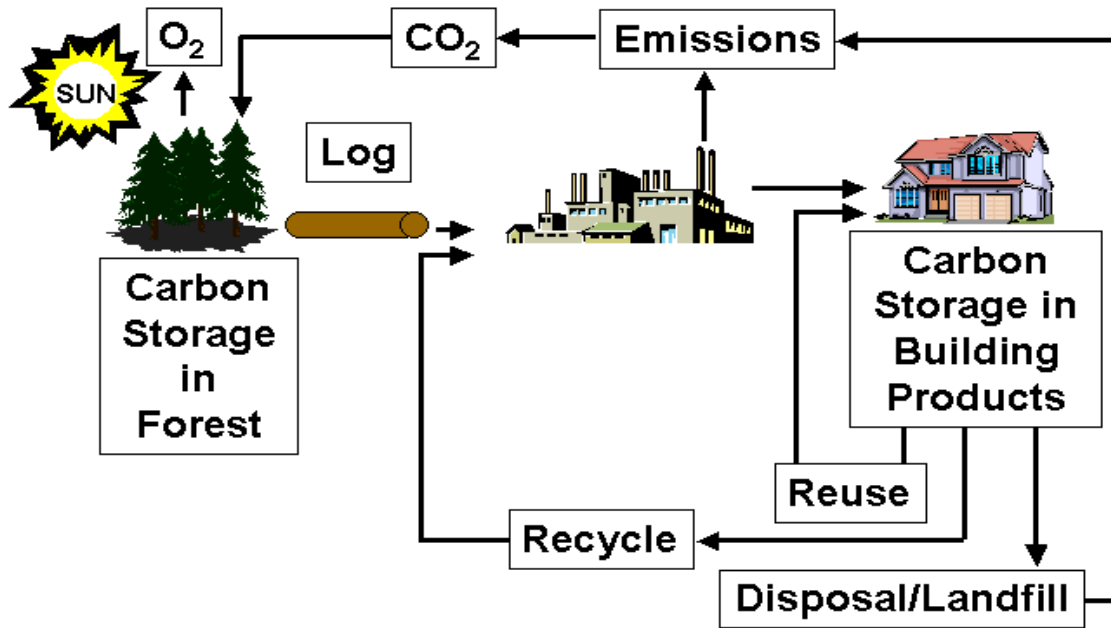


Figure 2.3. A Depiction of CORRIM Phase I Research

### 2.4.1 LCA Components

Table 2.1 and Figure 2.3 suggest that the LCA of a building system is a composite of many separate, but interrelated, LCAs. A building system LCA is created through cumulatively embedding the LCAs of many processes and their associated products, sub-assemblies and assemblies, each containing a specific set of life cycle stages from raw materials through recycling and waste management. For some products, certain stages may become deferred and be dependent on the aggregated LCA of the entire building of which they become a part. Examples are wall studs and other main framing lumber products that are covered by other materials and remain unchanged during the building life; these items typically have no maintenance stage of their own. Similarly, the recycling and disposal stage may apply to only some of the products when the building is finally demolished (i.e. recycling and disposal of these individual products is not separable from the building as a whole).

### 2.4.2 Initiation and Scope of Phase I

Construction of a complete residential home can be viewed as involving three categories of component LCAs. The first of these includes all of the products and assemblies required to produce the structural skeleton of the building. The second category involves additional products, such as siding, insulation, and roof topping, to complete the building envelope. The third category involves products and activities to complete the interior.

As noted earlier, the scope of Phase I CORRIM research is restricted to a study of a subset of the overall system. This subset includes:

1. Forest growth and harvesting and product manufacturing in the US Pacific Northwest and Southeast. These two regions are the predominant suppliers of domestically manufactured wood building materials.
2. Wood products and assemblies needed to create the closed-in building envelopes that meet the requirements of prevailing building codes in a warm climate (Atlanta, GA) and a cold climate (Minneapolis, MN).

Methods developed for these selected regions and codes will be refined and adapted to other regions in future work. Future research will also entail extending the analysis to interior finishing and nonstructural exterior work.

### **2.4.3 Inventory Analysis and Data Collection**

Many types of data can be acquired to estimate production and environmental performance measures for each process, all of which have been used to some degree by other life cycle researchers. However, it is important to distinguish between primary and secondary data. Primary data are those collected using recognized inventory data collection rules from specific facilities or operations; such data is typically labeled to indicate the date of collection and the estimated reliability of the data. Secondary data are those obtained from secondary sources such as simulation studies, or published articles containing industry or region-wide, or company specific information. The various areas of study within CORRIM are discussed in the following paragraphs, with commentary regarding the type of data collected.

#### *2.4.3.1 Forest Growth and Harvesting*

Production of output from a forest ecosystem involves activities associated with establishment and growth of trees and other vegetation, the removal of wood biomass used as input into product manufacturing processes, and associated impacts on non-wood forest co-products including water, habitat, diversity, and aesthetics. These impacts change through time due to basic tree and plant physiology and competitive stand dynamics, past and prospective technologies, evolving silvicultural practices, and population demands for forest outputs. Time is a critical element since the period from establishment to removal can vary from a few years for short rotation, intensive culture fiber/energy plantations to a century or more for selectively managed forests. Life Cycle inputs and outputs include both quantitative measures of productivity, costs, and environmental effects and qualitative measures that describe difficult to measure aspects of the forest environment.

Consideration of the environmental impacts to a forest requires a landscape approach since management levels of varying intensity, including no management, are applied differentially to sites of different productive capability and age classes that are often adjacent to one another. The blend of management intensities and age classes within a landscape is important in developing a balanced perspective on quantitative and qualitative outputs and effects. The approach taken by CORRIM with respect to forest growth and harvesting is to construct scenarios describing conditions associated with the growth, removal and establishment of forests for each region (Pacific Northwest, and Southeast) and to use forest simulation models to estimate the effect of site productivity and management intensity on the following two categories of measures.

- Quantities of products (sawlog, veneer log, pulp log), costs, resources consumed (energy, fertilizer, etc.), and associated emissions factors that are passed to the product manufacturing stage (Module A).
- Measures of effects on diversity and habitat, stream quality, etc. that are unique to the forest resource stage and provide indications of the impact of the forest activity (Module O).

All of the input and output data compiled by CORRIM Phase I research on forest growing and harvesting activities are based on regional forest growth and yield models and recent studies of harvesting systems reported in the literature. No direct field studies were commissioned by CORRIM however many field inquiries were made to verify the data and methods used.

#### *2.4.3.2 Product Manufacturing & Unit Processes*

An objective of Phase I is to treat each major step of each manufacturing process as a separate unit (“unit process”) for data collection. For example, a sawmill can be viewed as consisting of the following processing centers (or unit processes): log yard, debarking and bucking, primary breakdown of logs into trimmed, green lumber; kiln drying, planer mill, and grading and packaging. This level of detail allows for recognition of various product grades and joint products from each center that may be sold to other industries without further processing. It also recognizes alternative pathways of primary material through the mill (green lumber to grading & packaging versus green lumber to kiln drying). By performing data collection at the unit process level, many potential issues with respect to co-product allocation can be resolved and differences among various technological configurations for a unit process can be examined. Data for individual unit processes and facilities will vary by plant age and type, and factors such as transportation distances will also vary by region. Sampling individual facilities and unit processes provides a sense of the variation in the industry and permits summarization that provides the range, median, mode and upper/lower quartiles. This permits analyses that can focus on the sensitivity of outcomes to advances in adoption of technology such as indicated by the rhetorical question: “What happens as the industry gradually improves so the average moves up to the current upper quartile?”

CORRIM Phase I involved gathering of current data through questionnaires sent to selected individual manufacturers. Table 2.2 lists wood products and assemblies for which CORRIM data has been collected from manufacturers during Phase I (Modules B-H).

**Table 2.2. Wood Products for Which Unit Process Data has been Collected by CORRIM**

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Softwood lumber, kiln dried (US Southeast, US Pacific Northwest)
Softwood lumber, green (US Pacific Northwest)
Softwood plywood (US Southeast, US Pacific Northwest)
Oriented strandboard (US Southeast)
Glue laminated beams (US Southeast, US Pacific Northwest)
Laminated veneer lumber (US Southeast, US Pacific Northwest)
Wood “I” joists & beams (US Southeast, US Pacific Northwest)

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Construction of buildings also involves consumption of non-wood materials such as concrete for foundations and steel for nails and fasteners, etc. Life Cycle data for these materials and products were taken from previous Life Cycle studies compiled or conducted by the Athena Sustainable Materials Institute. Table 2.3 lists products for which CORRIM is using data from previously published LCAs during Phase I.

**Table 2.3. Products Considered in CORRIM Using Data from Studies**

Conducted by the Athena Sustainable Materials Institute

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<b>Material</b>	<b>Product Considered</b>
<b>Concrete</b>	<ul style="list-style-type: none"> <li>• 10, 15, and 20 MPA ready mix</li> <li>• Precast double T beams</li> <li>• Precast hollow deck</li> <li>• Standard concrete blocks</li> <li>• Cement mortar</li> </ul>
<b>Steel</b>	<ul style="list-style-type: none"> <li>• Painted trusses (bar joists)</li> <li>• Galvanized studs</li> <li>• Galvanized decking</li> <li>• Composite steel/wood joist components</li> <li>• Reinforcement bar</li> <li>• Painted hollow structural steel</li> <li>• Painted tubing</li> <li>• Painted heavy sections</li> <li>• Painted light sections</li> <li>• Hot &amp; cold rolled sheet</li> <li>• Welded wire mesh &amp; ladder wire</li> <li>• Nails and Fasteners</li> </ul>

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#### *2.4.3.3 Building Construction*

Construction of a building involves a fundamental shift from individual products to the combination of these into building assemblies (wall, floor, and roof systems) using spans, loads, and other variables that comply with building codes. The activities associated with construction include those involved in producing building materials, as well as new Life Cycle steps and impacts tied to construction activity in which materials and energy are consumed, and solid wastes and emissions are produced. Some effects are simply the aggregate of the various materials used in the construction assemblies while others are unique to the construction activities and are not attributable to an individual component product. To integrate various combinations of products into functionally equivalent assemblies and completed structures, CORRIM used the Environmental Impact Estimator (EIE model) of ATHENA™ which contains more than 50 different assemblies incorporating combinations of concrete, steel, and wood products. Working with ATHENA™ researchers, CORRIM developed additional structural designs based on residential building codes in Minneapolis, MN and Atlanta, GA to represent cold and warm climate conditions, respectively (Modules I and J).

#### *2.4.3.4 Building Use and Maintenance*

The structural materials and assemblies generally require little direct maintenance during the operational life of a building unlike siding, roofing and other assemblies required to fully complete the exterior of a building. Since the dominant exterior maintenance requirement is roofing which is common to all building designs examined, the environmental performance estimates for maintenance (Module L) do not identify different impacts for different framing methods and are relatively small compared to the impact of construction or building use.

Energy consumption during the operational life of the building and maintenance of the shell have been estimated based on the average home in each city hence providing a perspective on the relative importance of these stages on overall Life Cycle energy consumption and emissions (Module K and L).

#### *2.4.3.5 Building Demolition and Material Recycling or Disposal*

Recycling and waste management focus on the individual materials for which recycling and waste management opportunities differ greatly. Energy and emissions are involved in demolition/deconstruction, separation and transport of the materials, and in recycling and waste management processes. Since a building may not be demolished for many years after construction, accurate depiction of this stage would require forecasting technologies and markets for recycling and waste management far into the future. Since these conditions are unknown, CORRIM assumes that current practices are applicable (Module M). Furthermore, research suggests that demolition, recycling, and disposal differences between alternative designs are small (FORINTEK & Wayne B. Trusty 1997). Therefore, comparisons between design alternatives will be reasonably accurate in the absence of good data for this stage. However, when absolute effects of individual designs are required, better data for this stage may be necessary, a topic for future research. In particular, the recycling of finally disposed materials, which includes biofuel uses and the decomposition of materials from disposal in landfills is very problematic, requiring future research.

#### *2.4.3.6 Data Consistency for Building Use, Maintenance, Demolition and Material Recycling or Disposal Stage*

It should be noted that the data collected for energy use, maintenance and demolition is derived from models available from the literature and these models are therefore not totally consistent with the building designs used for the construction of a structure. The CORRIM primary focus is on the environmental performance issues with the products that make up the structure. We include the impacts from use, maintenance and disposal in order to provide measures of relative performance across all stages of processing. The impacts from maintenance and demolition are substantially smaller than for the constructed structure or building use, hence we do not provide complete LCI data (a deviation from the guidelines) but concentrate on the energy and carbon burdens that are most important for an analysis of cumulative effects across all stages of processing.

#### **2.4.4 Impact Assessment**

Impact assessment is presently at a rudimentary stage since the environmental and human health consequences of emissions are difficult to quantify in that they depend on temporal and geographical dispersion, level and rate of exposure, and other factors. The assessment interpretation step considers the inventory data as well as an analysis of the impact on human or ecological health. Some aspects of the CORRIM inventory analysis relate fairly directly to impact assessment. For example, quantities of concrete, steel, and wood consumed relate directly to resource depletion. At this point CORRIM research is not explicitly focused on impact assessment beyond inferences associated with energy, water and materials consumption and the use of widely accepted environmental equivalence measures for some categories of emissions (e.g. expressing various greenhouse gases in CO<sub>2</sub> equivalents or global warming potential).

The Life Cycle Product information developed by CORRIM on wood products was used with ATHENA™ Environmental Impact Estimator model (EIE) to extend the analysis from the produced product to a Life Cycle Assessment of residential construction (ATHENA™ 2004). The EIE model also contains source data for non-wood products, largely steel and concrete that can substitute for wood in some applications. The EIE model allows a designer to model a building or subassembly, generate the bill of materials needed, analyze the long list of inputs and outputs, and to aggregate the impacts into several risk indices for a comparative assessment on the pros and cons of using one product or design over another. The LCA risk indices analyzed in the EIE model include: embodied energy, global warming potential, solid waste, and air and water pollution. These indices allow one to compare product alternatives, which may be process dependent whether the products are made of wood or competing materials. Separately CORRIM has produced a forest ecology assessment associated with management alternatives for a renewable forest resource although there is no corresponding counterpart analysis for the depletion of non-renewable product alternatives.

The embodied energy index is based on all energy sources however the CORRIM report separately tracks bioenergy, hydro and fossil sources since they have different impacts. The global warming index uses EPA's equivalence factors for carbon dioxide, methane and nitrous oxides. The solid waste index is based on mass, which is the conventional metric used in LCA. While volume may be a relevant metric in some instances, an analysis of many sites would be required to convert from known product masses to transport volumes. The mass of air and water pollutants are not equally toxic hence these indices are computed on the basis of the worst offending substance by diluting each substance to their safe EPA standard. Value judgments are involved in any scheme to weight these indices. CORRIM provides both LCI data and these LCA indices, which can be used with any number of weighting schemes.

## **2.5 IMPROVEMENT ANALYSIS AND SCENARIOS**

Improvement analysis refers to using LCA results to suggest opportunities for environmental improvement or to evaluate proposed changes to a product, process, or design. Since improvement analysis often involves different technical expertise (process design engineers, product designers), and broader considerations (economic and market factors) than information gained from a Life Cycle study, it is often conducted independently of LCA or as an adjunct to an LCA. However, through sensitivity and scenario analyses and studying material substitutions, CORRIM research will provide comparisons and insights that will assist analysts, designers, managers, and policy makers in understanding relative benefits and costs associated with alternatives and understanding which stages and unit processes in the Life Cycle provide the greatest leverage for improvement.

## **2.6 TEMPORAL ISSUES IN THE LCA CONTEXT**

Many life cycle inventories are performed for non-durable products for which the time from resource extraction until post-consumer disposal was so short that the temporal distribution of events and associated impacts can be ignored. In contrast, the life cycle for CORRIM research covers a very long time frame, beginning with planting a forest stand, cultivating it to maturity, harvesting and converting logs into products that are assembled into buildings, tracking the activities during occupancy and use of the building until its eventual demolition and disposal. For CORRIM, the time dimension becomes great and presents difficulties that are not well discussed in the LCA literature. Some activities, such as the growth of a forest stand and associated carbon removals from the atmosphere and the consumption of energy for heating and cooling of a building, occur in relatively small annual quantities; the aggregate total when trees are harvested or when a building is demolished would be misleading since the totals and associated emissions did not occur in these specific single event years. Other events such as fertilization of the forest or re-roofing a building only occur at intervals so a total, expressed as if these events occurred simultaneously does not make sense. To properly deal with the timing of events and emissions and avoid misleading aggregations, CORRIM developed a method for portraying the Life Cycle as a series of cohorts (forest stand and building age classes) that move through time. Correct accounting at any time point is the sum of the activities and emissions of those cohorts that coexist at that time. To illustrate, consider a simplified CORRIM Life Cycle consisting of the following phases:

### **1. Forest Planting and Growth**

Carbon removal from the atmosphere and sequestration occurs annually through the growth phase that may take 25 to 100 years or more until harvest. Cultural activities and wood marketed from thinning occur periodically. Consider the following forest age cohorts and associated cultural activities:

- Nursery: planting seed, irrigating, fertilizing and packaging/shipping for planting
- Stand initiation: site preparation, planting seedlings on the forest site, weed control
- Early stand culture: weeding, pre-commercial thinning, fertilizing, pruning
- Middle stand culture: commercial thinning, fertilizing
- Mature stand: final harvest

Unlike many LCAs of wood products, the CORRIM perspective, that includes forest growing, considers harvested logs as an intermediate product rather than the starting raw material. Raw materials in the CORRIM perspective are air, water, and solar energy used in photosynthesis, land, and fertilizers and fuels associated with the silviculture and harvesting activities.

## 2. Harvesting, Product Manufacture, and Building Construction

The series of conversion and building processes from “stump to completed structure” that commonly takes 2 years or less

## 3. Building Occupancy and Use

Building occupancy and use consumes annual energy for lighting, heating, and cooling plus periodic maintenance events. The building may be used for 25 to 100 years or more. Consider the following building age cohorts:

- **Young:** relatively little maintenance, replacement, or remodeling occurs during the early use of a new home.
- **Middle-aged:** the first cycle of maintenance and replacement activities begins; hence there is demand for materials to accomplish them as well as disposal issues for the replaced materials.
- **Old-aged:** maintenance and replacement cycles may intensify as the house becomes outdated and homeowners undertake various remodeling steps.

### 2.6.1 Time-line Perspective of Cohorts

Figure 2.4 portrays the "cradle-to-grave" perspective for the cohorts with the time-line shown underneath; "h" is the age when the forest is harvested and "T" is the time when the building is demolished. The problem with the time-line perspective is that it creates some logic issues and violates the tenet that LCI is based on empirical, not forecast data. At any time chosen as the present, data for all activities beyond that time point are forecast data that must rely on assumptions regarding changes in technology and design. If the present is assumed to be the time of planting seed, can we assume that today's building codes, design practices, and materials will be relevant when the home is built from these trees at h+2 years in the future? If not, what will the relevant codes, designs, and materials be? If thinnings are conducted, is it logical to pool them with the final harvest as inputs into the "stump to structure" stage? In the real world, no mill stores thinnings from a stand for 15 or 20 years in order to process them with the logs from the final harvest of that stand.

----- Forest Growth -----						----- Building Use -----			
N	P	PTF'	PTF	M	S/S	Y	M	O	D
N	P	Prune	Prune	M	Stump to Structure	Y	M	O	D
u	a	Thin	Thin	a		o	i	l	i
r	n	Fert	Fert	t		u	d	d	s
e	t			u		n	e		p
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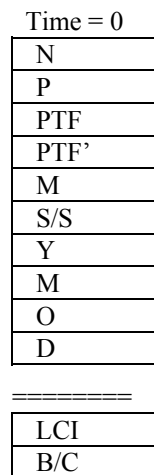
**Figure 2.4. The Time-Line of the CORRIM Life Cycle**

To illustrate a different type of problem, consider the final disposal of the building. The disposal, materials recovered, and emissions to the environment of a new building that will not be built until far into the future, and which will not be torn down until much later, are likely to be very different than the problems associated with tearing down and disposing of materials from the today's obsolete buildings. A question to be raised is "are we really interested in the cumulative impacts associated with planting seeds in a nursery and, perhaps 200 years into the future, tearing down and disposing of a building made from them?"

## 2.6.2 Simultaneous Cohort Perspective

The difficulties with the time-line approach in Figure 2.4 can be overcome by recognizing that all cohorts exist simultaneously in a single time period (Figure 2.5). Today, nurseries are producing seedlings for planting on lands that were just harvested, there exists a mix of forest age classes receiving silvicultural treatments (pruning, thinning, fertilization), some are producing logs from thinnings and some from final harvesting for manufacturing processes that produce products, subassemblies and housing developed with known, current technologies and design methods. Owners of relatively new buildings are dealing with relatively minimal upkeep and repair; owners of, say, 15-30 year old buildings, are involved in many maintenance activities using current materials and code requirements; owners of much older homes are dealing with the unique problems they present; and some of the existing housing inventory is being demolished and replaced. The environmental impacts of demolition of today's obsolete homes reflect the actual materials of the past that were used to build and maintain them. This includes problems such as lead-based paints and asbestos that will not be used in future designs but are impacting current disposal and recycling options and will continue to have an impact in the near future.

Summation of activities performed on today's stocks of forest lands and housing, coupled with today's processing, construction, and demolition and disposal methods, provides a more realistic "bottom line" inventory report on the current status of resource and energy consumption and releases to the environment. Furthermore, empirical data can be collected on each of these activities because they are occurring now. Thus all data is empirical in the true spirit of a Life Cycle inventory. Similarly, it is relatively easy to collect data on current costs of labor, capital, raw materials (both virgin and recycled) and energy associated with each activity and on market prices for products and develop benefit/cost information. CORRIM has adopted this perspective and used data gathered from current technologies that are applied to currently existing forest and housing cohorts. This means that CORRIM associates data from activities in current nursery, stand initiation, early-, middle, and mature stand cohorts to the current volume of timber extracted. Similarly, occupation and use and demolition data from activities in current housing is associated with the new building structures.



**Figure 2.5. Simultaneous Cohorts in the CORRIM Life Cycle System**

*Note:* See Figure 2.4 for definition of symbols

## 2.7 SCENARIO ANALYSES: POLICY CHANGES AND ECONOMIC LINKAGES

If one wishes to study the effect of a policy change, such as lengthening forest rotation cycles to store additional carbon, this can be easily accommodated with the cohort approach. Implementing such a policy would alter forest practices whereby each of today's age classes in Figure 2.5 initiates a process where that class evolves over time in response to practices that would implement the policy (Figure 2.6). Thus, the young stands that were just thinned and fertilized in the present will evolve toward maturity over time under the influence of this policy.

				<i>N=&gt;</i>
			<i>N=&gt;</i>	<i>P=&gt;</i>
		<i>N=&gt;</i>	<i>P=&gt;</i>	<i>PTF=&gt;</i>
	<i>N=&gt;</i>	<i>P=&gt;</i>	<i>PTF=&gt;</i>	<i>PTF'=&gt;</i>
<i>N=&gt;</i>	<i>P=&gt;</i>	<i>PTF=&gt;</i>	<i>PTF'=&gt;</i>	<i>M=&gt;</i>
<i>P=&gt;</i>	<i>PTF=&gt;</i>	<i>PTF'=&gt;</i>	<i>M=&gt;</i>	<i>S/S=&gt;</i>
<i>PTF=&gt;</i>	<i>PTF'=&gt;</i>	<i>M=&gt;</i>	<i>S/S=&gt;</i>	<i>Y=&gt;</i>
<i>PTF'=&gt;</i>	<i>M=&gt;</i>	<i>S/S=&gt;</i>	<i>Y=&gt;</i>	<i>M=&gt;</i>
<i>M=&gt;</i>	<i>S/S=&gt;</i>	<i>Y=&gt;</i>	<i>M=&gt;</i>	<i>O=&gt;</i>
<i>S/S=&gt;</i>	<i>Y=&gt;</i>	<i>M=&gt;</i>	<i>O=&gt;</i>	<b>D</b>
<i>Y=&gt;</i>	<i>M=&gt;</i>	<i>O=&gt;</i>	<b>D</b>	
<i>M=&gt;</i>	<i>O=&gt;</i>	<b>D</b>		
<i>O=&gt;</i>	<b>D</b>			
<b>D</b>				
0 ..... time ..... T				
LCI <sub>0</sub>	LCI <sub>1</sub>	....	....	LCI <sub>T</sub>
B/C <sub>0</sub>	B/C <sub>1</sub>	....	....	B/C <sub>T</sub>

**Figure 2.6. Temporal Progression of Cohorts in the CORRIM Life Cycle**

*Note:* See Figure 2.4 for definition of symbols

Large bold cells represent pathways (left to right) from present age classes of forestlands and housing. Bold italic cells represent pathways based on future plantings after stocks of existing forests are harvested.

At any point in time, the evolving forest yields logs from thinning and final harvest that are processed by industry into products, subassemblies, and houses. The changes in forestry to accommodate the policy may alter the quantity, size, and quality of the logs available to industry thereby forcing changes in processes, products, and designs, which create new homes for occupancy. Concurrently, maintenance, replacement, repair/remodel, and demolition/disposal are continuing on older homes produced in previous periods. Thus the effect of a policy produces changes in the forest, which in turn have lagged effects on the characteristics of materials, which later may affect technologies used, products and design. By forecasting these changes to a time of interest in the future and summing the columns for the time periods, one can obtain inventory summaries and summarize the costs, revenues, and other benefits that occur. These “bottom line” summaries can then be compared in terms of change in physical parameters of interest and in terms of economics.

This approach, in which cradle-to-grave aspects of forest products are regarded as simultaneously occurring cohorts, allows analysts to develop a valid Life Cycle-inventory status report on the current situation, develop economic measures of the current situation, and then use forecasting techniques and sensitivity analysis to estimate how changes in any system element lead to changes in environmental and economic measures over time.

This perspective provides a means for reconciling difficulties with temporal aspects of Life Cycle inventories associated with forestry and housing and provides a means by which the tool of Life Cycle inventory can be used in conjunction with the tools of economic analysis. It is also consistent with the approach commonly used by individual firms in applying and combining Life Cycle inventory and improvement analysis methods in identifying cost-effective ways to provide products with improved environmental performance.

### **3.0 PHASE I ACCOMPLISHMENTS**

The section describes the accomplishments achieved in Phase I in summary form. A major accomplishment is the preliminary environmental assessment for the construction of a single family building shell. Other accomplishments include life cycle inventories for wood and other processes that produce the materials and energy used to construct the single-family shell. Detailed information on these processes has not been available until now. Phase I also initiated research into other processes that have yet to be addressed elsewhere including carbon inventory measurements and dynamic issues associated with forest resources.

One of Phase I's major realizations is the preliminary environmental assessment for a building shell using two sets of different materials. Five indices are constructed and used to summarize the many output measures from the LCI on the building shell. The indices measure embodied energy, greenhouse warming potential, air pollution, water pollution and solid waste emissions. All measures for which there were significant differences (more than 5-10%) indicate lower burdens for the wood design in both Minneapolis and Atlanta. While insignificant in magnitude, the Minneapolis steel design produces about one percent less solid waste (one tonne) than the wood design and for Atlanta there is no difference in water pollution. One can infer from the environmental assessment that the wood designs generally result in lower energy and pollution measures.

To complete the environmental assessment Phase I produced LCI information for forest resources; lumber; plywood; oriented strand board; gleam; I-joists; LVL; an integrated LCI/LCA for the building structure; an LCI for building use, maintenance and disposal; an ecological integrity index for the forest and a time series analysis of carbon from the forest into products, including the impact of biofuels and energy substitution via product substitution.

The Forest Resource module provides the environmental, energy and resource impact data on the growth, management, harvesting and reforestation of timber for the Pacific Northwest (PNW) and Southeast (SE) regions of the US for representative acres within each region (Module A). The study calculates volume harvested for three general combinations of management intensity and site productivity for each region. The combinations were reduced to a single estimate of yield using weighting factors developed for this research. The weighting scheme creates a base case for each region. Alternative weights, such as more acres under a higher level of management intensity, produce an alternative case, with a different calculated volume. For example, the increase in merchantable volume under the more intensively managed alternative case was 31% in the Southeast (including volume from the second rotation when rotation ages are reduced) and 16% in the Pacific Northwest. The portion of lumber and pulpwood produced in the Southeast changed under the alternative scenario; lumber output share increased 9.2 percentage points and pulpwood decreased a like amount. The alternative scenario also leads to a 7.0% decrease in the average rotation age in the Southeast. Lumber output increased 66% in the Southeast. Lumber output share remained at 100% in the base and alternative PNW scenarios.

System costs increased by 36% compared to the 31% volume increase in the Southeast; however, the shorter rotation may more than offset that increase in a discounted cash flow analysis. System costs increased about the same percent as merchantable volume removed in the PNW. A similar result is observed for fuel and lubricant consumption during harvesting operations: a 33% increase in the Southeast and 17% increase in the PNW roughly corresponding to the changes in merchantable volumes harvested, although there appears to be a slight increase in the consumption factors in the Southeast due to the change in rotation age and products harvested. The increase in harvested volume resulted from using 3 times more nitrogen and phosphate in both the Southeast and the PNW as fertilizer inputs in conjunction with the other management changes.

Along with harvested volumes, the study also produces harvesting cost data and air emission estimates related to stand growth and harvesting. Resources used to produce the harvested volume, such as fuel, fertilizer and herbicides, are quantified and their impacts reported in the Environmental Impact Report during the extraction phase of the single family shell construction.

The Forest Resource Module also produces estimates of tree biomass by component. These estimates are used to approximate the standing and removed carbon pool over time. Indices of stand structure and diversity are developed for the Westside of Washington using a landscape approach to forest management as proxies for changing ecological integrity (Module O). As a consequence of prior regulatory changes and federal land management policies, all scenarios show some restoration of diverse forest structure that had been declining. More intensive management involving thinnings improves restoration by reducing overly dense stands. Longer rotations enhance old forest structures but at a substantial economic cost.

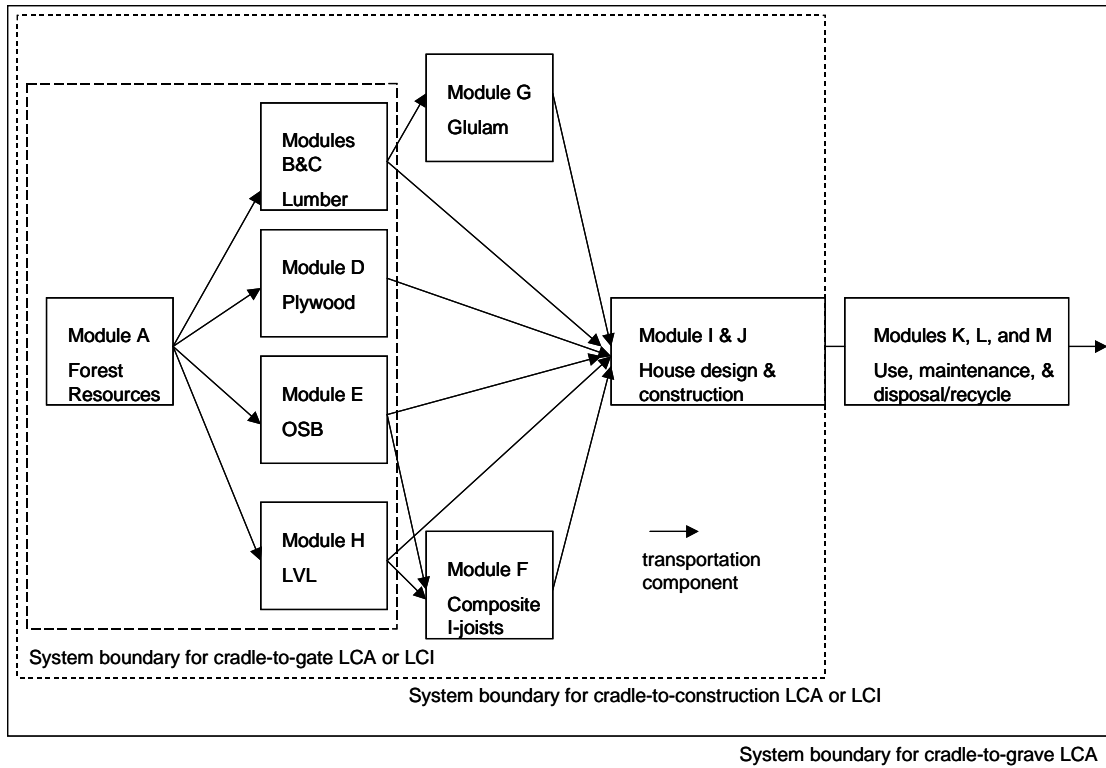
Harvested volumes from the two forest resource regions are passed on to lumber manufacturers in the Pacific Northwest and Southeast regions. Here the research developed independent LCIs for the two regions. The two regional lumber manufacturing modules were developed to provide the environmental, energy and resource impact data on the manufacturing of softwood lumber. In the Northwest a survey produced the data on sawing, drying and planing processes with a supplemental survey on boiler operations. The unit process approach produces detailed descriptions of activities and the resource used to produce specific outputs. For example, the sawing process involves log sorting and storage, their delivery to debarkers, and bucking to length. The debarked, bucked logs are sawn into rough lumber producing pulp chips, bark and sawdust as co-products. The rough lumber is transported within the mill to stacks for kiln dryer or planer facilities, two additional processes with their corresponding activities. To accomplish the sawing activity maintenance work on equipment and vehicles are also recorded, as well as treatment processes of air, liquids and solid materials. The result of the survey work produced detail information that was then analyzed with the SimaPro life cycle program (PRé 2001). The SimaPro analysis consisted of four processes, adding energy generation to the three processes mentioned above. The result of the analysis produces unit factor estimates for one Mbf of planed dry lumber. These unit factor estimates include raw material usage, airborne waterborne and solid emissions, and energy usage (Module B).

The Southeastern lumber module produces similar type of data (Module C). Harvested volumes from the two forest resource regions are also passed on to softwood plywood manufacturers in the Pacific Northwest and Southeast regions (Module D). The research module for softwood plywood production produces the life cycle inventory data used in the LCI for the building shell. A survey was implemented in a manner similar to the lumber manufacturing modules. The plywood process was defined in terms of six processes: bucking and debarking, block conditioning, peeling and clipping, drying, lay-up and pressing, and trimming and sawing. The result of the survey work produced detailed information that was then analyzed with the SimaPro life cycle program. The result of the analysis produces unit factor estimates for one Msf of 3/8-in basis of plywood.

Similarly an LCI was developed for Oriented Strandboard (OSB) production in the southeast (Module E). From these product LCIs and additional survey information, LCIs for the production of I-joists, glulam beams, and LVL were also developed (Modules F, G, and H). Information was also collected on log transport, production of phenol-formaldehyde and MDI resins and wax as inputs to the manufacturing and construction processes. The environmental and energy impact data were recorded and passed along to the construction phase of the research.

In addition to the product LCIs reported in modules A-H and the LCI/LCA developed for the buildings structure in module J, LCIs for building use, maintenance and final disposal were developed (Modules K, L, and M). Information on the useful life of residential buildings was developed within the Maintenance Module (L). While each module provides some sensitivity analysis, an integration of the energy use and carbon measures across all stages of processing are summarized in these final sections of the report.

When determining the various LCIs and LCAs, see Figure 2.7 for a schematic of the system boundaries to use for a given scenario. For example, to determine the cradle-to-gate LCI of manufacturing a given product, i.e., plywood, cumulative data would be determined by summing the forest resource Module A LCI data, with the LCI transportation data that would be determined based on the delivery mileage in plywood Module B, with the LCI manufacturing data in plywood Module D. To determine the LCI for a cradle-to-construction scenario, the cumulative data would be determined by summing the cradle-to-gate LCI for all the wood products used in the construction of the house, with the LCI transportation data based on the delivery mileage and mode of transport from the manufacturing facility to the construction site which is given in Module J, and then using ATHENA<sup>TM</sup> software to include the LCI of the non-wood materials used in the construction and the LCI data for the construction. The resulting cradle-to-construction LCI can then be used to determine the associated cradle-to-construction LCA as given in Module J.



**Figure 2.7. System boundaries used to determine various LCI and LCA values based on LCI data in each report Module**

#### 4.0 ENERGY USED ACROSS THE LIFE CYCLE OF A RESIDENTIAL BUILDING

Modules J-M describe the energy used in representative residential buildings across their life cycle. The energy used to produce the construction materials and build the house are provided in module J, heating and cooling energy over the life of the building in module K, energy for maintenance in module L, and the energy used in demolition in module M. Table 4.1 summarizes the energy used for each life cycle stage. The energy used in heating and cooling dominates the energy used in all other stages of the life cycle. However from an economic standpoint, since the energy used in heating and cooling is spread over the 75-year life cycle, the present value cost is a relatively small share of the total construction investment.

Since there is an insignificant difference in the heating and cooling energy used between different framing methods and these differences could be reduced to zero by small design changes such as the use of insulation, table 4.1 adopts the energy use for heating and cooling for the wood framing unit as the standard regardless of the impact from different materials used in framing. By far the largest maintenance requirement is the roof, which was common for all framing designs studied, so again only the maintenance for the wood framing design is shown. For demolition there is a slightly higher use of energy for the heavier and bulkier concrete structure.

**Table 4.1 Energy used in representative building life cycle stages**

	Minneapolis House		Atlanta House	
	Wood Frame	Steel Frame	Wood Frame	Concrete Frame
Energy in the Structure (GJ)	646	759	395	456
Energy from Maintenance (GJ)	73	73	110	110
Energy for Demolition (GJ)	7	7	7	9
<b>Energy Subtotal (GJ)</b>	<b>727</b>	<b>840</b>	<b>512</b>	<b>573</b>
<i>House Cost</i>	<i>\$168,000</i>	<i>\$168,000</i>	<i>\$135,000</i>	<i>\$135,000</i>
<i>Construction Cost</i>	<i>\$92,000</i>	<i>\$92,000</i>	<i>\$74,000</i>	<i>\$74,000</i>
<b>Energy Use</b>				
<b>heat &amp; cool (GJ)</b> (75 yrs)	<b>7800</b>	<b>7800</b>	<b>4575</b>	<b>4575</b>
<i>Cost/yr heat &amp; cool</i>	<i>\$692</i>	<i>\$692</i>	<i>\$491</i>	<i>\$491</i>
<i>Present Value Cost</i> (75 years @ 5%)	<i>\$13,490</i>	<i>\$13,490</i>	<i>\$9565</i>	<i>\$9565</i>
<b>% of Construction \$</b>	<b>14.7</b>	<b>14.7</b>	<b>12.9</b>	<b>12.9</b>

While the energy use for heating and cooling is roughly ten times the energy used in construction, maintenance and demolition, the cost is less than 1/7th the cost of construction. Reducing energy use to zero is a Department of Energy objective. One could spend an additional \$13,490 on the Minneapolis house or \$9,565 on the Atlanta house to reach that objective at an interest cost of 5% (adjusted for inflation). Reducing the energy in construction is sensitive to the design of the building and the processing efficiency of materials with the wood frame construction substantially more efficient than using fossil intensive substitutes like steel and concrete.

#### **4.1 ENERGY COMPARISONS FOR PRODUCTS BEING SUBSTITUTED**

While the total embodied energy in the steel frame house was 759 GJ compared to 646 GJ for the wood frame house the contribution of wood products to this number is very small. When we look only at the steel, wood and insulation being substituted, the energy for these products, less bio-energy which is internally generated and renewable, are: 164 GJ for the steel frame (22% of the total) and 43 GJ for the wood frame (7% of the total). The explanation for this much reduced energy consumption is the high energy intensity of the products other than wood, steel and insulation that is common to both houses such as the energy in concrete, glass, gypsum and asphalt roofing. While the total energy in the steel house is only 17% greater than the wood house, for the products being substituted the steel frame uses 281% more non-bio energy than the wood frame. The substitution of steel and insulation for wood increases the non bio-energy in steel and insulation by 127 GJ with only a 7 GJ decrease in the energy to produce the wood. While the steel frame uses much more energy than the wood frame, the energy used by products other than steel and wood that are common to both designs is substantially greater.

Similar comparisons for the concrete house show 461 GJ embodied energy compared to 398 GJ for the wood house. Looking only at the concrete and rebar, which substitutes for wood in the concrete house, the energy used less bio-energy are: 84 GJ for the concrete frame (18% of the total) and 24 GJ for the wood frame (6% of the total). While the total energy in the concrete frame is only 16% greater than the wood house, for the products being substituted the concrete frame uses 250% more non-bio energy than the wood frame. The substitution of concrete block, mortar and rebar requires 63 GJ more energy while the wood energy use decreases by only 3 GJ. Similar to the steel comparison, the concrete frame uses much more energy than the wood frame but the energy in products common to both designs including the concrete floor and foundation are substantially greater.

## 5.0 INTEGRATED LIFE CYCLE ASSESSMENT FOR CARBON FROM CRADLE TO GRAVE

While most life cycle assessments are performed for products for which the time from resource extraction until post-consumer disposal is so short that time intervals can be ignored, the life cycle for CORRIM research covers a very long time frame with a focus on renewable materials rather than non-renewable extraction and very durable long-lived structures. Activity begins with planting a forest stand, managing it to maturity, harvesting and converting logs into products that are assembled into buildings, tracking the activities during occupancy and use of the building until its eventual demolition and disposal. To deal with the timing of events and emissions and avoid misleading aggregations, a method for portraying the life cycle as a series of cohorts (forest stand and building age classes) that move through time was created (see Sections 2.6 and 2.7). The forest management activities are represented by a full rotation of the forest so that the sum of the activities and emissions for each age cohort is represented i.e., there is one unit of the forest at age 1, 2... to the harvest age, as the end of the rotation. Since carbon represents one of the more important environmental contributions of the forest, carbon sequestration and emission in the forest is integrated with carbon emission and storage in processing, building construction, building use, and final demolition in Table 5.1.

**Table 5.1 Carbon sequestration, storage and emissions in representative building life cycle stages**

CO <sub>2</sub> Tonnes	Minneapolis House		Atlanta House	
	Wood Frame	Steel Frame	Wood Frame	Concrete Frame
Emissions in mfg Construction & Demo	37.1	46.8	21.4	28.0
Emissions from biofuel	3.6	2.6	3.4	2.7
Emissions from Maintenance	3.4	3.4	4.1	4.1
Emissions from heating & cooling	390	390	232	232
<b><i>Subtotal of Sources</i></b>	<b><i>434</i></b>	<b><i>443</i></b>	<b><i>261</i></b>	<b><i>267</i></b>
Forest Sequestration	(467)	(246)	(103)	(85)
Wood product storage	(22.4)	(11.8)	(17.1)	(14.1)
<b><i>Subtotal of Storage</i></b>	<b><i>(489)</i></b>	<b><i>(258)</i></b>	<b><i>(121)</i></b>	<b><i>(100)</i></b>
<b>Net Emissions</b>	<b>(55)</b>	<b>185</b>	<b>140</b>	<b>167</b>

To integrate across carbon contributions the sources of emissions in manufacturing, and building use are considered first followed by the sources for carbon storage in the forest and wood products. The sources of carbon emissions from product manufacturing, construction of a house and demolition which includes harvesting and all transportation amount to 37 tonnes of emissions for the Minneapolis wood frame construction, 47 for steel frame, 21 for the Atlanta wood frame and 28 for concrete frame construction. Biofuel emissions are added as a separate line since by the normal convention, bioenergy is CO<sub>2</sub> neutral and was not included in manufacturing as a contribution to carbon emissions. This avoids double counting with the carbon stored in the forest. These emissions are small in comparison; 3.6, 2.6, 3.4, and 2.7 tonnes respectively.

We next consider emissions associated with the maintenance of the structures. These impacts are small (3.4 tonnes of emissions for Minneapolis and 4.1 for Atlanta). The differences between framing methods are insignificant since roof maintenance is by far the largest activity when maintaining the structure and the roofing system is common across framing methods.

We next add the emissions from heating and cooling over the 75-year life of the house; 390 tonnes of CO<sub>2</sub> for Minneapolis and 232 tonnes for Atlanta. While the concrete and steel framing methods consumed more energy and emitted more CO<sub>2</sub> than the wood designs, these differences are a result of not fine tuning the design to produce equal effectiveness in thermal efficiency, hence the wood frame results are used throughout.

The carbon stored in the forest and products represents an increase in carbon storage provided by the land allocated to support a constructed house including the carbon exported into products. We calculate the acres required to support the construction, use, maintenance and demolition activities by dividing the forest rotation age (from module A) by the number of houses that can be produced from the volume of wood products that are processed from a harvested acre adjusted for the expected 75-year life of the house (modules I & J). The calculation results in 5.5 acres in use to support the Minneapolis wood frame, 2.6 acres for the steel frame, 8.1 acres for the Atlanta wood frame, and 7.0 acres for the concrete frame. Forest carbon, is reduced by the percentage of co-products serving other uses as derived in modules B-H resulting in 467 tonnes less CO<sub>2</sub> emissions which have been removed from the atmosphere and stored in the forest for the Minneapolis wood frame structure, 246 for the steel frame, 103 for the Atlanta wood frame, and 85 for the concrete frame. In effect, substituting non-wood materials reduces the acres that would be sustained under forest management resulting in a reduction in the corresponding carbon sink. The shorter rotations in the south result in less forest sequestration for the Atlanta houses.

As timber is removed from the forest and products are produced, the carbon in products continues to be stored for the life of the house. The carbon stored in the products offsets 22 tonnes of emissions for the Minneapolis wood frame construction, 12 for steel frame, 17 for Atlanta wood frame and 14 for concrete frame.

While the total source of emissions is dominated by energy used in heating and cooling, the forest and wood product sinks and stores for carbon tend to be larger for the Minneapolis wood frame house. The net CO<sub>2</sub> reduction is 55 tonnes for the Minneapolis wood frame house including all sources of emissions and sources of carbon storage. For the steel house there are net emissions of 185 tonnes, 140 for the Atlanta wood frame, and 167 for the concrete frame, i.e., only the Minneapolis wood frame shows more carbon stored than emissions. These stocks of carbon dioxide exist across the life of a house and the effective rotation of the forest such that if when a house is removed it is replaced they become permanent stocks associated with a permanent housing service unit.

We do not account for the slow and partial decomposition of the carbon stored in products after demolition since they occur well outside of the useful life stage of the house. If when the house is demolished, the waste wood products were burned for energy value the displacement of fossil energy sources would provide a more than offsetting carbon credit for the emissions from burning. However if landfilled, which remains the dominant disposal method in the US, that portion that decomposes would reduce the carbon stored in products. This does not alter the relative rankings of total storage for the comparisons shown and also remains outside of the time period for the useful life of the house. Future research is needed to better characterize the impact of final product disposal while noting that these processes will likely change substantially over time.

Integration over all of the activities performed on today's stocks of forest lands and housing, coupled with today's processing, construction, and demolition and disposal methods, provides a realistic "bottom line" inventory report on the current status of resource and energy consumption and releases to the environment. However efforts to identify cost effective improvements may need to take into consideration the time value of money which differs across several of these life cycle stages.

An alternate perspective more closely linked to forest management tracks the carbon over time, in the forest, in both short- and long-lived products, in biofuel displacement of fossil energy and product substitution. Unlike the above lifecycle analysis that characterizes a snapshot of all activities and assumes stability, the time series analysis developed in module N shows that while the carbon in the forest approaches stability, the carbon in products continues to grow as does the carbon displacement from the substitution of wood for fossil intensive products. The displacement of fossil intensive products is a very important factor in full carbon accounting.

## 6.0 RAW MATERIAL UTILIZATION EFFICIENCY

Increasing the efficiency of raw material utilization can be as important in improving environmental performance as other process or product improvements. Changing process technologies have for many years reduced wood waste, providing the same supply of wood products from less acres of forestland.

**Oriented Strandboard (OSB):** OSB uses different species than plywood with fewer co-products, reducing the acres needed to produce a building while also shifting the supply to species and forests that are in lower demand. A large portion of the 425 million cubic ft. of OSB produced in the US in 2003 is derived from forestland that was not producing solid sawn wood thereby representing a large increase in raw material utilization efficiency while also increasing the forest acreage being managed sustainably.

**Wood I-joists:** The substitution of wood I-joists for sawn solid wood is summarized in Module J. The LCI (environmental performance) differences for the materials to produce a house are not large but there is a significant reduction in wood fiber used. It requires only about 62% to 65% of the mass of wood to make I-joists relative to sawn wood. I-Joists are pre-cut resulting in less waste. They also provide increased stiffness that may reduce the required dimensions. Using the I-joists only in floor joists results in 1.3 tonnes less wood fiber (10%) used in construction of the house. This has the same impact as increased forest productivity i.e. it takes less acres to supply the same housing demand.

**Use of lower grade species:** In addition, the engineered I-joist generally uses OSB, a lower cost fiber source not suitable for solid sawn lumber with less fiber waste per acre of forestland. This increases the efficiency of use through the increased availability of lower valued species and a greater portion of the volume removed is used in high valued construction grade products. To the degree that the capacity of wood production is limited by the amount of land available for softwoods, a reasonable first approximation, all of these changes directly increase the output of construction grade wood products from the same softwood supply base. Quantifying this kind of utilization efficiency gain was not attempted, as it would require a more precise categorization of species by acre than was available.

**Intensive management:** More intensive management provides another scenario for increased raw material utilization efficiency by providing more wood and products per acre of supply. For the Southeastern supply region, dominated by non-industrial private forests, by shifting the management intensity class from low to mid-range and those in the mid-range to high, 31% more timber would be forthcoming but with 66% more lumber as more intensive management produces larger logs. The opportunities for intensive management would be somewhat less in the Northwest with more industry land already intensively managed. A shift of 18% of the acres in low intensive management to mid range and 24% from mid-range to high produced 16% more timber with the same increase in lumber.

In general, even when the substitution of OSB or I-joists for solid sawn softwood may appear to have only a small impact on the direct product LCI, there will likely be a substantial gain in raw material utilization efficiency.

## 7.0 ENVIRONMENTAL IMPROVEMENT OPPORTUNITIES

Many opportunities for environmental improvement have been noted including management, process and material substitution. There may of course be internal tradeoffs between environmental burdens with some rising while others fall. There may also be cost tradeoffs that need to take into consideration the time value of money. The report identifies many areas where environmental performance improvement is possible. Those opportunities that would appear to have a substantial improvement potential and benefit from further analysis using the LCI information in this report include:

- Redesign of the house to use less fossil intensive products
- Redesign of the house to reduce energy use (both active and passive)
- Revising building codes to reduce excessive use of products
- Greater use of low valued wood fiber for biofuel
- Greater use of engineered products producing higher valued products from less desirable species while also using less material per unit of construction
- Improved process efficiencies such as the boiler or dryer (including air drying)
- Environmental pollution control improvements evaluated using LCI/LCA
- More intensive forest management
- Recycling demolition wastes
- Increased product durability (given the already long expected life of a house, from 75-100 years, this applies primarily to moisture/weather exposed areas)

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## **APPENDIX A**

### **EXTERNAL REVIEW OF THE CORRIM PHASE I FINAL REPORT**

Conducted by:

Dr. Frank Werner, Environment & Development, Waffenplatzstrasse 89, CH-8002 Zurich, Switzerland

#### **SCOPE OF THE REVIEW**

An independent external two stage desktop review was conducted to assess the conformity of the CORRIM Phase I Final Reports with the applicable standards for life cycle inventories ISO 14'040 and ISO 14'041 as well as with the CORRIM Phase I research guidelines (Briggs 2000). A thorough first review of the draft reports was made in spring 2004 and included the executive summary, the research guidelines and the module reports A to M. This first round should ensure that:

- The methods used to carry out the data collection and compilation are consistent with the series of standards ISO 14'040ff (where applicable)
- The data used are appropriate and reasonable in relation to the goals of the reports
- The study report is transparent and consistent.

The module reports N and O do not contain life cycle inventory data. These reports were checked for transparency, scientific soundness and plausibility of the results.

A detailed list of recommended and requested modifications, and methodological remarks were sent to the authors for revision of their reports. The second review was made in November 2004 and covered only the life cycle data related part of the revised main report and the life cycle inventory data containing modules A to J. The original module reports K, L and M were integrated into one report for the second review, which was conducted in May 2005. The following evaluation is the result of this second review.

#### **REVIEW METHODOLOGY**

The main report and each module report were checked using a form with a detailed list of criteria. These criteria were derived previously from the structure and requirements of the standard ISO 14'041.

Separate forms were filled in for:

- Building product-related module reports, summarizing the review findings of the module reports A to H
- Cradle-to-construction site comparison of different residential structures (module reports I and J)
- Integrated module report K, L, and M covering the energy consumption and greenhouse gas emission related to the use, maintenance and demolition of residential structures

These forms can be found as detailed results of the review process as an annex to this text.

In addition to the review procedure according to ISO 14'040, the consequences of methodological settings of the CORRIM research guidelines or as applied in single module reports were analyzed. A summary of these findings is presented in the section 'Further findings and recommendations' further down; a reply to some of these remarks by the CORRIM research team can be found in section 1.5 of the CORRIM phase I research report. These methodological issues do not affect ISO-conformity of the module reports; they should be kept in mind if the LCI data of this study is used in comparative LCAs.

## **FINDINGS AND EVALUATION**

CORRIM phase I research has generated an internationally outstanding, extensive, methodologically consistent dataset for the production chain of wood products in the Southeast and Pacific Northwest of the United States.

As a result of my two-stage desktop review I herewith confirm that the CORRIM phase I module reports:

Module A: Forest resources – Pacific Northwest and Southeast (June 2004)

Module B: Softwood lumber – Pacific Northwest region (June 2004)

Module C: Softwood lumber – Southeast region (June 2004)

Module D: Softwood plywood manufacturing (June 2004)

Module E: Southeastern oriented strandboard production (June 2004)

Module F: Composite I-joists – Pacific Northwest and Southeast (July 2004)

Module G: Glued laminated beams – Pacific Northwest and Southeast (June 2004)

Module H: Laminated veneer lumber – Pacific Northwest and Southeast (June 2004)

provide representative, transparent, complete, scientifically and methodologically sound life cycle inventory data for different wood based products used in building construction in line with the goal and scope of the CORRIM phase I research plan. The module reports are in conformity with the applicable standards ISO 14040 and ISO 14041.

The CORRIM phase I module reports:

Module I: Design of residential building shells – Minneapolis and Atlanta (August 2004)

Module J: Environmental impacts of a single family building shell – from harvest to construction (September 2004)

provide a transparent, complete, scientifically and methodologically sound life cycle inventory data and environmental impact assessment for different, functionally equivalent housing constructions from raw material extraction to the raw constructions ('from cradle-to-gate') in line with the goal and scope of the CORRIM research. This comparison has been made and is documented in conformity with the applicable standards ISO 14040, ISO 14041 and ISO 14042.

The CORRIM phase I module report:

Modules K, L and M (integrated): Energy consumption and greenhouse gas emissions related to the use, maintenance and disposal of residential structures (June 2005)

provides representative, transparent, complete, scientifically and methodologically sound partial life cycle inventory data (primary energy and greenhouse gas emissions) for the energy consumption and transport emissions related to heating, cooling, maintaining and residential structures in line with the goal and scope of the CORRIM research. The study report is in conformity with the applicable standards ISO 14'040 and ISO 14'041.

The research summary report:

Phase 1 research report on the research plan to develop environmental performance measures for renewable building materials with alternatives for improved performance (June 2005),

provides a comprehensive summary of the research activities undertaken under the CORRIM phase I research plan. The results shown in this summary, which are based on the module reports A to M, are based on methodologies, data compilation procedures and documents in conformity with the applicable standards ISO 14'040 and ISO 14'041.

## **FURTHER FINDINGS AND RECOMMENDATIONS**

The following findings and recommendations discuss some methodological settings and structural particularities of the life cycle data inventories of the CORRIM research phase I. They should enable external users of the datasets to assess the suitability of the datasets for their own purposes; they are also intended as a contribution to the methodological discussion for the CORRIM research phase II and to a possible specification of the CORRIM research guidelines (Briggs, 2001). They do, however, by no means affect the ISO conformity of the module reports A to J.

Some general methodological issues are discussed in the following points:

- The CORRIM research guidelines prescribe mass- (or volume-) based allocation factors for the allocation of joint co-production processes. Mass-based allocation is a widespread allocation routine and is in conformity with ISO 14040ff. However, it should be taken into account that in the wood-chain, mass-based allocation attributes less environmental burdens to sawn timber and other wood products than would correspond to their relative share of revenues. This leads to a 'favorable' inventory for timber and derived products compared to an allocation based on economic value. Besides sawn timber, this question is relevant for all wood products with a relatively low conversion factor, i.e. a high output of further co-products. For example, this is the case for plywood

or glued laminated timber (because of the timber production process). Given the large differences in revenues for the main product of a specific process in the wood chain compared to its co-products such as bark, chips, sawdust, etc., this methodological setting can be significant and should to be taken into account in comparative LCAs.

- The cut-off procedure (e.g. Fava & Denison, 1991) is applied for the modeling of recycling material input and output. This procedure is in conformity with the ISO 14041 allocation procedure for reuse and recycling and is in fact used frequently in large databases. Although often used for LC inventories and LCA studies, the application of the cut-off procedure in an LCA can lead to higher environmental burdens than other ISO-conform allocation procedures, and finally to misleading recommendation for environmental improvements (Werner, 2005; Werner & Scholz, 2002). This is particularly true for metals with expanding markets (Werner, 2005). When the environmental impacts of the whole life cycle of the buildings are investigated in detail during the CORRIM research phase II, the modeling of recycling material should be evaluated in a sensitivity analysis, particularly in the case of the steel construction.
- A further methodological prescription of the CORRIM research guidelines is relevant for the further use of the LCI datasets of the CORRIM Phase I report: the exclusion of the energy content of biogenic materials in products. Not taking the energy content for biogenic materials into account, especially construction wood, might underestimate the ‘waste of energy carriers’ if wood is not burned for thermal energy purposes after service life but dumped into a landfill. This limits the incentive to use post-consumer waste wood as a fuel for the substitution for fossil energy carriers. The energy content of biogenic material is relevant also in the context of the contribution of wood products to the mitigation of climate change. It has been shown in other studies that the additional pool capacity of wood products (‘sink capacity’) in buildings is of minor importance; the far more important are substitution effects caused by the substitution for energy-intense alternative materials and by the substitution for fossil fuels due to a consequent thermal energy recovery of industrial and post-consumer waste wood (Werner *et al.*, 2005). This carbon-energy correlation is neglected with the exclusion of the energy content of biogenic materials.

The following points include some more specific remarks on specific methodological and formal issues with regard to CORRIM research guidelines and the module reports A to J:

- In accordance with the CORRIM research guidelines, forestry processes, the transportation of logs and the transportation of ancillary materials (adhesives, resins, intermediate wood products, etc.) have not been taken into account in the product life cycle datasets. This is a particularity of the CORRIM datasets and has to be carefully considered if the datasets are included into an LCA software. CORRIM’s use of ATHENA™ EIE as the LCA software does incorporate these burdens correctly.
- These particular system boundaries lead to the fact that cumulated data inventories (adding up all impacts from cradle-to-gate) can hardly be used for comparisons with other studies. To enable such comparisons, the documentation of the input data for an LCA software per functional unit would be of much more interest. This type of data is not provided in all module reports. For the CORRIM research phase II, I recommend providing the following datasets to enhance transparency and to improve the utility for other readers:
  - Plant data, i.e. fuels and electricity, ancillary materials and semi-finished products, emissions from processes and combustion, transportation (type and size of vehicle, distance), co-products and waste fractions; this data is not allocated (in

the sense of ISO 14'041)

- Input data to an LCA software per functional unit; this data is allocated
- Cumulated inventory data of on-site and off-site environmental interventions caused by the functional unit under study
- Some of the reports are not entirely in conformity with the CORRIM research guidelines. One report includes facility heating in the data (which might in fact be a requirement of the production process) (module G); another report includes electricity consumption of the administrative department (module E); and in one report (module E), process data is allocated to bark mulch as co-product, whereas bark is considered a by-product in the CORRIM research guidelines (appendix). However, these (small) methodological deviations are not considered to have significant impacts on the over-all result; ISO-conformity is not affected.
- Some modules (e.g. module G) use hogged fuel as input from outside the plant under study. In the LCA software used for the inventory analysis, a module for hogged fuel from the software database is used to model the respective environmental burdens. I am not familiar with the Franklin data base, from which the module is taken. However, if this module contains industrial waste wood as the source it should be checked if this hogged fuel comes with environmental burdens from previous production processes or if it is modeled according to the cut-off procedure (only transports are attributed to the hogged fuel). If it does not come with environmental burdens, the mass-based allocation is not uniformly applied throughout the study. However, given the small share of imported hogged fuel, this methodological issue does not have a significant impact on the over-all result. This issue is also not relevant if the hogged fuel is produced in the forest. If the import of hogged fuel becomes relevant during the CORRIM research phase II, I recommend defining a module for hogged fuel, based on the weighted hogged fuel generation throughout the wood chain that is covered by the CORRIM research (see also Hischier *et al.*, 2004).
- Solid waste on a mass-basis is used as an impact indicator in module J. It is stated in the module report that volume-based considerations could alter the results. In any case and given the different processing options for solid waste – landfill, recycling, incineration, etc. – it would be more appropriate to indicate different types of solid waste fractions in dependency of their further treatment: 1 tonne of recyclable steel should be valued differently than 1 tonne of mixed bricks and concrete. For waste going to a landfill, volume would indeed be a more appropriate unit, as space is usually the limiting factor in landfills.
- I suggest updating the CORRIM research guidelines with regard to the formal requirements of ISO 14'041 and the experiences of the Phase I research. Such formal requirements include the documentation of data quality issues, data representativeness, the dealing with blank and zero-values including plausibility check of reported data, the structuring of the data to be reported, the documentation of the system boundaries, etc.

*Dr. Frank Werner*

*Zurich, December 15, 2004*

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## REVIEW FORM: CONFORMITY WITH ISO 14040FF

**Module A: Forest resources – Pacific Northwest and Southeast, by Johnson, L.R., Lippke, B., Marshall, J.D. and Cornick, J, version June 2004**

**Module B: Softwood lumber – Pacific Northwest region, by Milota, M.R., version June 2004**

**Module C: Softwood lumber – Southeast region, version, Milota, M.R., West, C.D. and Hartley, I.D., June 2004**

**Module D: Softwood plywood manufacturing, by Sakimoto, E.T. and Wilson, J.B., version June 2004**

**Module E: Southeastern oriented strandboard production, by Kline, D.E., version June 2004**

**Module F: Composite I-joists – Pacific Northwest and Southeast, by Dancer, E.R. and Wilson, J.B, version July 2004**

**Module G: Glued laminated beams – Pacific Northwest and Southeast, Puettmann, M.E. and Wilson, J.B., version June 2004**

**Module H: Laminated veneer lumber – Pacific Northwest and Southeast, Dancer, E.R. and Wilson, J.B, version July 2004**

**Reviewer: Frank Werner, Environment & Development, Zurich**

**Date: 10 December, 2004**

Module report J provides 'cradle-to-gate' life cycle inventory data for two pairs of functionally equivalent residential building shells, which have been designed in module report I.

Subject	Review comment	Compliance
<b>GENERAL ASPECTS</b>		
LCA commissioner, practitioner of LCA	Stated	√
Date of report	Stated	√
Reference to the series of standards ISO 14'040ff	Stated	√
<b>GOAL OF THE STUDY</b>		
Reasons to carry out the study	In section 1; in conformity with the CORRIM research guidelines	√
Its intended applications	In section 1; in conformity with the CORRIM research guidelines	√
The target audience	In section 1; in conformity with the CORRIM research guidelines	√

SCOPE OF THE STUDY		
Modifications together with their justification	Not applicable	-
Function	Commercial standard units of wood products	√
Statement of performance characteristics	Described in each module report as characterisation of the co-product	√
Any omission of additional functions in comparisons	Not relevant for modules B – H; forestry provides a variety of environmental services, which are disregarded in module A	√
Functional unit	Described appropriately	√
Consistency with goal and scope	Consistent	√
Definition	Processes described in detail	√
Result of performance measurement	Not applicable	-
Functional equivalence (in comparative studies)	Not applicable	-
System boundaries	In conformity with goal and scope of the study; according to the CORRIM research guidelines: plant analysis leading to an analysis providing on-site and off-site generated LCI data (excluding transport and forestry processes)	√
Inputs and outputs of the system as elementary flows	According to the CORRIM research guidelines	√
Decision criteria	According to the CORRIM research guidelines (< 2% of total mass, no environmental significance)	√
Omissions of life cycle stages, processes or data needs	Cradle-to-gate analysis Infrastructure and plant administration are excluded; forestry processes and all transports to production facility are disregarded (modules B – H)	√
Initial description of the unit process	Some production plants are looked at as black boxes; other ones are subdivide into specific production processes	√
Decision about allocation	Mass-based co-product allocation; according to CORRIM research guidelines	√
Data categories	According to CORRIM research guidelines	-
Decision about data categories	According to CORRIM research guidelines	√
Details about individual data categories	According to CORRIM research guidelines	√
Quantification of energy inputs and outputs	According to CORRIM research guidelines; embodied energy for wood used as material is not accounted for	√
Assumptions about electricity production	Regional electricity production mixes are assumed and described in each module report	√
Combustion heat	Fuel type, moisture content for wood (u=50%) and boiler efficiency are taken into account	√
Inclusion of fugitive emissions	Included according to CORRIM research guidelines	√
Criteria for initial inclusion of inputs and outputs	Inputs and outputs are included according to the cut-off criteria of the CORRIM research guidelines.	√

	Description of criteria and assumption	According to the CORRIM research guidelines (< 2% of total mass, no environmental significance)	√
	Effect of selection on results	Not investigated	-
	Inclusion of mass, energy and environmental criteria	Resources, intermediate products, energy carriers, wastes and emissions into air, water and soil are considered; according to the CORRIM research guidelines	√
	Data quality requirements	Representative data from CORRIM survey 2001	√
	Time-related coverage	Year 2000	√
	Geographical coverage	Stated in reports	√
	Technological coverage	Average regional technology	√
	Precision completeness and representativeness of the data	Samples with different statistical representativeness	√
	Consistency and reproducibility of the methods used throughout the LCA	Guaranteed by the CORRIM research guidelines and the documentation in the report	√
	The sources of data and their representativeness	According to the CORRIM research guidelines; plan surveys as primary data source complemented with specific, larger surveys to cover energy generation where necessary; literature as secondary data source	√
	Uncertainty of the information	According to the CORRIM research guidelines	√
	Type and format of the report required for the study	Not applicable	-
<b>INVENTORY ANALYSIS</b>			
	Procedures for data collection	CORRIM survey based on questionnaires; complemented with secondary literature	√
	Qualitative and quantitative description of unit processes	Production processes are described in detail	√
	Sources of published literature	Literature is referenced appropriately	√
	Calculation procedures	Average regional data inventories are calculated with an LCA software. Calculation procedures are transparent and understandable. However, the modelling of the plant data in the LCA software is not documented in all module reports.	√
	Validation of data	Plausibility checks and cross-comparison of data from different regions were conducted according to the CORRIM research guidelines	√
	Data quality assessment	Mass-balances were set up; they show very low discrepancies	√
	Treatment of missing data	Zero-values and missing data are consistently reported in most module reports. No major data gaps are reported. Minor data gaps such as the modelling of ancillary materials are covered with plausible assumptions	√
	Sensitivity analysis for refining the system boundaries	Not applicable	-
	Allocation principles and procedures	Documented appropriately	√
	Documentation and justification of allocation procedures	Allocation problems resulting from joint co-production in the wood chain are solved on unit process level by allocating on a mass-basis. The mass-based allocation procedure is documented and justified as response to the review text in section 1.5 of the main report.  Regional electricity mixes are used and documented.  Allocation related to recycling is not relevant in the module reports A – M	√

	Uniform application of allocation procedure	Co-product allocation procedures are uniformly applied. However, the definition of by-products in the CORRIM research guidelines is not uniformly applied; this does not affect ISO conformity, nor is the impact considered to be significant.  Imported hogged fuel is modelled using data from the Franklin Associates database. Consistency with the CORRIM modelling could not be checked during this review.	√
<b>LIMITATIONS OF LCI</b>			
	Data quality assessment and sensitivity analysis	According to the CORRIM research guidelines	√
	Precision	Survey data as best available data	√
	Completeness	The collected data is very extensive.  Some energy balances do not state internally produced electricity separately.  The energy content of wood products is disregarded. As a consequence of the latter, the land filling of wood does not result in the (useless) 'consumption' of an energy carrier if whole life cycles of wood products are modeled. This has to be taken into account if this inventory data is used for comparative LCAs.	√
	Representativeness	The representativeness of the survey data differs; representativeness of the data is stated in all module reports. No limitation is described for the research area.	√
	The system functions and functional unit(s)	No limitations detected	√
	The system boundaries	System boundaries are consistent with the goal and scope of the CORRIM research guidelines.  The module reports do not include forestry processes or the transport of logs and ancillary materials to the production plants.	√
	Uncertainty analysis	Sensitivity analysis is conducted to investigate the influence of some assumptions and production characteristics.  The influence of further 'uncertain' parameters such as moisture content for incineration processes or wood densities is not investigated.	√
	Limitations identified by the data quality assessment and sensitivity analysis	No limitations are identified by the data quality assessments and sensitivity analysis with regard to the goal and scope of the reports	√
	Conclusions and recommendations	Conclusions are well-founded by the results of the inventory and its analysis and are addressing the goal and scope of the reports	√
<b>IMPACT ASSESSMENT (if applicable); see ISO 14'042, chap. 10 for details</b>			
	Results	Not applicable	-
	Methodology	Not applicable	-
<b>INTERPRETATION (if applicable)</b>			
	Results	Not applicable	-
	Assumptions and limitations associated with the interpretation of results	Not applicable	-
	Methodology related	Not applicable	-
	Data related	Not applicable	-

CRITICAL REVIEW (IF APPLICABLE)		
Name and affiliation of reviewer	Mentioned in main report	√
Review procedure	Mentioned in all module reports	√
Critical review reports	Included in main report	√
Responses to recommendations	Included in main report	√

## REVIEW FORM: CONFORMITY WITH ISO 14040FF

**Module I:** Design of residential building shells – Minneapolis and Atlanta (August 2004), by Kasal, B. and Huelman, P., version August 2004

**Module J:** Environmental impacts of a single family building shell – from harvest to construction, by Meil, J., Lippke, B., Perez-Garcia, J., Bowyer, J. and Wilson, J.B, version September 2004

**Reviewer:** Frank Werner, Environment & Development, Zurich

**Date:** 10 December, 2004

Module report J provides ‘cradle-to-gate’ life cycle inventory data for two pairs of functionally equivalent residential building shells, which have been designed in module report I.

Subject	Review comment	Compliance
<b>GENERAL ASPECTS</b>		
LCA commissioner, practitioner of LCA	Stated	√
Date of report	Stated	√
Reference to the series of standards ISO 14'040ff	Stated in the introduction and separate guidelines	√
<b>GOAL OF THE STUDY</b>		
Reasons to carry out the study	Stated in the introduction	√
Its intended applications	Stated in the introduction	√
The target audience	Stated in the introduction	√
<b>SCOPE OF THE STUDY</b>		
Modifications together with their justification	Not applicable	-
Function	The scope of the study is a cradle to construction site analysis of two pairs of different functionally equivalent housing constructions designed for two regions of the U.S.	√
Statement of performance characteristics	The housing designs and performance characteristics of the housings are described in a separate report (module I report)	√
Any omission of additional functions in comparisons	The functional equivalence only refers to the average size and thermal properties. Further aspects like economics or aesthetics are not taken into account.	√
Functional unit	Not applicable in a strict sense, as no life cycle of a product is considered.	√
Consistency with goal and scope	The focus on the cradle to construction site analysis is consistent with the goal of the study	√

Definition	Characteristics and material balances of the different housing types are sufficiently described in sections 2.4 and 3.1.	√
Result of performance measurement	Not applicable	-
Functional equivalence (in comparative studies)	Not applicable	-
System boundaries	In conformity with goal and scope of the study; according to the CORRIM research guidelines	√
Inputs and outputs of the system as elementary flows	'Cradle-to-construction site', including construction itself and transport to construction site	√
Decision criteria	According to the CORRIM research guidelines as applied in the modules A – H. (< 2% of total mass, no environmental significance); cut-off procedure applied for recycling material (see module report J, section 2.1)	√
Omissions of life cycle stages, processes or data needs	Maintenance, use and demolition are treated in separate module reports K – M; a preliminary summary 'cradle-to-grave' is provided in the main report	√
Initial description of the unit process	Unit process boundaries are described for wooden building materials in modules A – H. For the constructed house, data of four data life cycle stages is provided: manufacturing, manufacturing transport, construction, and construction transport. Boundaries for these stages are described in the background section of module J. Boundaries for steel and concrete materials are characterized in the description of the Athena™ software as these are secondary data categories for this project.	√
Decision about allocation	Allocation of burdens for wood is provided in section 2.2 – Integrating CORRIM LCI Data. Allocation for steel and concrete materials are summarised in section 2.1 and described in the description of the Athena™ software as these are secondary product data categories for this project.	√
Data categories	According to CORRIM research guidelines	√
Decision about data categories	According to CORRIM research guidelines	√
Details about individual data categories	According to CORRIM research guidelines	√
Quantification of energy inputs and outputs	According to CORRIM research guidelines; heat value of wood used as construction material is disregarded	√
Assumptions about electricity production	Considering specific electricity production mixes, as described in section 2.2 – Integrating CORRIM LCI data	√
Combustion heat	As modelled in the module reports A – H and as modelled in the LCA software	√
Inclusion of fugitive emissions	Included according to CORRIM research guidelines	√
Criteria for initial inclusion of inputs and outputs	Inputs and outputs are included according to the cut-off criteria of the CORRIM research guidelines	√
Description of criteria and assumption	Described in the CORRIM research guidelines	√
Effect of selection on results	Not investigated as state-of-the-art criteria are applied	-
Inclusion of mass, energy and environmental criteria	Resources, energy consumption, wastes and emissions into air and water are considered; according to the CORRIM research guidelines	√
Data quality requirements	Defined in the CORRIM research guidelines	√
Time-related coverage	For wood: primary mill survey data collected in 2000 and supplemented in 2001 For other materials and processes: Franklin Associates database (data from 1990s)	√

Geographical coverage	a) Atlanta and b) Minneapolis residential structures from Pacific Northwest and Southeast supply regions and regional specific mill processing	√
Technological coverage	Housing construction standard defined in module I to meet regional construction codes reflecting average regional technology	√
Precision completeness and representativeness of the data	Average, complete dataset	√
Consistency and reproducibility of the methods used throughout the LCA	Guaranteed by the CORRIM research guidelines and the documentation in the report	√
The sources of data and their representativeness	Module reports A – H. The data used for the alternative materials and non-wooden building parts, its representativeness and sources are not described directly but available through the ATHENA™ EIE model documentation which includes LCI reports for non-wooden materials. The references of the database are trustworthy	√
Uncertainty of the information	According to the CORRIM research guidelines	√
Type and format of the report required for the study	Not applicable	-
<b>INVENTORY ANALYSIS</b>		
Procedures for data collection	No in-plant data collection has been made for this module report. Data collection for the module reports A – H has been conducted according to the CORRIM research guidelines	√
Qualitative and quantitative description of unit processes	Described adequately	√
Sources of published literature	Literature is referenced appropriately	√
Calculation procedures	Calculation procedures are sufficiently clear, wood materials listed for each construction are taken from their respective LCI modules and the process of using the LCI product level data is described in section 2.2 'Integrating CORRIM LCI Data'	√
Validation of data	Material inputs and outputs for the mill were checked for mass balances and were generally within 1-2% as described in modules B – H.	√
Data quality assessment	Lacking but discussed in a response to reviewer recommendations	√
Treatment of missing data	As described in the module reports; model assumptions and expert guesses	√
Sensitivity analysis for refining the system boundaries	Not applicable	-
Allocation principles and procedures	Described in section 2.2 'Integrating CORRIM LCI Data'	√
Documentation and justification of allocation procedure	Provided in CORRIM research guidelines and section 2.2 of module J	√
Uniform application of allocation procedures	Wood-related allocation is uniformly applied throughout module reports A – H. Some wood modules import hogged fuel, which is modelled with data taken from the LCA software; uniform application of allocation procedures is not necessarily given. In any case, the impacts on the overall result are insignificant.  For alternative materials and fuels, data is taken from the Franklin database; data in this database is assumed to be consistent	√
<b>LIMITATIONS OF LCI</b>		
Data quality assessment and sensitivity analysis	The range of LCI impacts are available for products in modules A – H but not carried through the construction of a house. The impacts of a change in the level of wood	√

	residues used for biofuels are believed to be most sensitive and were examined.	
Precision	Precision of the LCA index measures are discussed in section 2.3.2. Precision for product LCIs are believed to be much better given the small discrepancies in mass balances which are described in each product LCI module.	√
Completeness	Very few gaps in inputs or outputs are identified. Data accuracy while reflective of primary survey data for wood products have not been fully evaluated and it is noted in the conclusion that improvements can be expected through more extensive use.	√
Representativeness	A pair of average housing constructions for the two regions under study are considered. The PNW and SE supply regions for products are the largest US supply regions	√
The system functions and functional unit(s)	In line with goal and scope of the study	√
The system boundaries	System boundaries are consistent with the goal and scope of the study (see above)	√
Uncertainty analysis	Not conducted	√
Limitations identified by the data quality assessment and sensitivity analysis	Aspects discussed in section 5.5 of module J	√
Conclusions and recommendations	Conclusions are well-founded by the results of the inventory and its analysis and are addressing the goal and scope of the study.  Caution is raised in the conclusions that allocation methods other than mass may produce somewhat different results although a critical sensitivity analysis on using co-products for energy reduces the purchased energy induced burdens for wood products.	√
<b>IMPACT ASSESSMENT; see ISO 14'042, chap. 10 for details</b>		
Results	Described in section 5	√
Methodology	Global warming potential, air and water indexes are used as impact categories; the calculation routines are described in section 2.3 of module J. In addition to these impact criteria, solid waste (in kg) and embodied energy are discussed.	√
<b>INTERPRETATION</b>		
Results	LCI data and LCIA data are interpreted in the respective sections	√
Assumptions and limitations associated with the interpretation of results	Described where applicable	√
Methodology related	It is stated that volume-based accounting of solid waste could alter conclusions	√
Data related	None	√
<b>CRITICAL REVIEW</b>		
Name and affiliation of reviewer	Stated in the main report; review mentioned in module reports	√
Review procedure	Internal and external review procedures are described in the main report	√
Critical review reports	Not mentioned	√
Responses to recommendations	Detailed recommendations provided by reviewers were generally responded to directly and included in the final report or explained in section 1.5 of the main report as CORRIM's response to review comments	√

## REVIEW FORM: CONFORMITY WITH ISO 14040FF

**Modules K, L and M (integrated):**

**Energy Consumption and Greenhouse Gas Emissions Related to the Use, Maintenance and Disposal of Residential Structures by Paul Winistorfer, Zhangijing Chen, Bruce Lippke, and Nicole Stevens (version May 2005)**

**Reviewer: Frank Werner, Environment & Development, Zurich**

**Date: 30 June 2005**

The integrated module report K, L and M covers the energy consumption related to heating, cooling, and occupying, as well as maintaining and disposing of different residential houses in Atlanta and Minneapolis in a life cycle perspective.

Subject	Review comment	Compliance
<b>GENERAL ASPECTS</b>		
LCA commissioner, practitioner of LCA	See above	√
Date of report	See above	√
Reference to the series of standards ISO 14'040ff	Mentioned	√
<b>GOAL OF THE STUDY</b>		
Reasons to carry out the study	Stated in the introduction; according to CORRIM research guidelines	√
Its intended applications	Stated in the introduction; according to CORRIM research guidelines	√
The target audience	Internal use; according to CORRIM research guidelines	√
<b>SCOPE OF THE STUDY</b>		
Modifications together with their justification	not applicable	-
Function	The scope of the study is the energy consumption related to heating, cooling, and occupying, as well as maintaining and disposing of different residential houses in Atlanta and Minneapolis	√
Statement of performance characteristics	References are made to relevant standards. Modelling parameters and assumptions are clearly described.	√
Any omission of additional functions in comparisons	The omission of not structure-related uses (laundry, cooking, lightning, etc.) for heating/cooling and non structural components (carpets, interior paints, washer, dryer, refrigerator, etc.) is clearly described.	√
Functional unit	The functional units - energy consumption for heating and cooling, - maintenance and replacement	√

	- deconstruction and transports to landfill are clearly described for the two regions and constructions under study	
Consistency with goal and scope	The focus on the service life of the construction with regard to the above-mentioned points complements the previous module reports and is consistent with the goals of the CORRIM research	√
Definition	Building characteristics are describe in Module I of the CORRIM phase I report, which is referenced appropriately; modelling parameters for the energy requirements are sufficiently described	√
Result of performance measurement	Not applicable	√
Functional equivalence (in comparative studies)	Functional equivalence is given for the Atlanta structures and assumed for the Minneapolis structure, as no calculation routine for a steel structure was available	√
System boundaries	In conformity with goal and scope of the study; according to the CORRIM research guidelines	√
Inputs and outputs of the system as elementary flows	According to the CORRIM research guidelines	√
Decision criteria	According to the CORRIM research guidelines (< 2% of total mass, no environmental significance)	√
Omissions of life cycle stages, processes or data needs	Cradle-to-grave analysis for the energy carriers Long-term emissions from landfills and infrastructure are disregarded	√
Initial description of the unit process	The unit processes are sufficiently described	√
Decision about allocation	In accordance with the CORRIM research guidelines	√
Data categories	According to CORRIM research guidelines	-
Decision about data categories	According to CORRIM research guidelines	√
Details about individual data categories	According to CORRIM research guidelines	√
Quantification of energy inputs and outputs	According to CORRIM research guidelines	√
Assumptions about electricity production	A regional electricity production mix is assumed and described in Chap. 6.0; according to CORRIM research guidelines	√
Combustion heat	Thermal energy generation processes are modelled in SimaPro; they consider fuel type and boiler efficiency.	√
Inclusion of fugitive emissions	Included according to CORRIM research guidelines	√
Criteria for initial inclusion of inputs and outputs	Inputs and outputs are included according to the cut-off criteria of the CORRIM research guidelines.	√
Description of criteria and assumption	According to CORRIM research guidelines	√
Effect of selection on results	Not investigated	-
Inclusion of mass, energy and environmental criteria	Resources, intermediate products, energies, wastes and emissions into air, water and soil are considered; according to the CORRIM research guidelines	√
Data quality requirements	Defined in the CORRIM research guidelines.	√
Time-related coverage	1998 (year of the Franklin Associates' database) and actual Census data	√

Geographical coverage	1) Atlanta/Georgia 2) Minneapolis/Minnesota	√
Technological coverage	Average regional technology	√
Precision completeness and representativeness of the data	Modelled data based on assumptions	√
Consistency and reproducibility of the methods used throughout the LCA	Modelled data based on assumptions	√
The sources of data and their representativeness	Modelled data based on assumptions and literature for secondary data	√
Uncertainty of the information	According to the CORRIM research guidelines	√
Type and format of the report required for the study	Not applicable	-
<b>INVENTORY ANALYSIS</b>		
Procedures for data collection	Use of secondary literature	√
Qualitative and quantitative description of unit processes	Relevant energy consumption processes are adequately described	√
Sources of published literature	Literature is referenced appropriately	√
Calculation procedures	Model assumptions are adequately described and the software used for the calculations is provided	√
Validation of data	According to the CORRIM research guidelines	√
Data quality assessment	The data quality is in conformity with goal and scope of the study.	√
Treatment of missing data	Zero-values and missing data are consistently reported. No major data gaps are reported.	√
Sensitivity analysis for refining the system boundaries	Not applicable	-
Allocation principles and procedures	According to the CORRIM research guidelines	√
Documentation and justification of allocation procedure	The CORRIM research guidelines are referenced	√
Uniform application of allocation procedure	The cut-off allocation for recycling materials is uniformly applied	√
<b>LIMITATIONS OF LCI</b>		
Data quality assessment and sensitivity analysis	According to the CORRIM research guidelines	√
Precision	Modelled data base on virtual housing designs; in accordance with goal and scope of the study	√
Completeness	The modelling covers the most relevant energy consumptions; in accordance with goal and scope of the study	√
Representativeness	Region-specific modelled data based on virtual housing designs; in accordance with goal and scope of the study	√
The system functions and functional unit(s)	In line with goal and scope of the study	√

The system boundaries	System boundaries are consistent with the goal and scope of the study. However, infrastructure and long-term emissions from landfills are disregarded. In addition to that, the use of the cut-off procedure for recycling materials can have significant impact on the result (particularly for the steel structure)	√
Uncertainty analysis	No uncertainty analysis is done but stated as a research need for the CORRIM Phase II.	√
Limitations identified by the data quality assessment and sensitivity analysis	Different energy analysis models are used for the construction phase and the use phase; however, data quality of this study is sufficient for the goal of this study.  The data quality of this report differs considerably from the previous module reports, which is mainly related to the necessary assumptions on service life and on required maintenance. Data should not be used for the comparison of different structures but is intended to provide an idea on the relevance of the life stages of this report with regard to the construction of the buildings.	√
Conclusions and recommendations	Conclusions are reasonably founded by the results in dependency of goal and scope of the study.	√
<b>IMPACT ASSESSMENT (if applicable); see ISO 14'042, chap. 10 for details</b>		
Results	Not applicable	-
Methodology	Not applicable	-
<b>INTERPRETATION (if applicable)</b>		
Results	Not applicable	-
Assumptions and limitations associated with the interpretation of results	Not applicable	-
Methodology related	Not applicable	-
Data related	Not applicable	-
<b>CRITICAL REVIEW (IF APPLICABLE)</b>		
Name and affiliation of reviewer	Stated in the main report; review mentioned in module reports	√
Review procedure	Internal and external review procedures are described in the main report	√
Critical review reports	Not mentioned	√
Responses to recommendations	Detailed recommendations provided by reviewers were generally responded to directly and included in the final report or explained in section 1.5 of the main report as CORRIM's response to review comments	√