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Comparison of the Life Cycle Assessments of a Concrete Masonry House and a Wood Frame House

by Medgar L. Marceau and Martha G. VanGeem

5420 Old Orchard Road
Skokie, Illinois 60077-1083
847.966.6200 Fax 847.966.9481

www.cement.org

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ABSTRACT

This report is an update of *Life Cycle Assessment of an Concrete Masonry House Compared to a Wood Frame House* (Marceau and VanGeem 2002). It presents the results of an assessment of the environmental attributes of concrete construction compared to wood-framed construction. A life cycle assessment (LCA) was conducted on a house modeled with two types of exterior walls: a wood-framed wall and a CMU wall. The LCA was carried out according to the guidelines in *International Standard ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. The house was modeled in five cities, representing a range of U.S. climates: Lake Charles, Tucson, St. Louis, Denver, and Minneapolis

The 228-square meter (2450-square foot), two-story, single family house has four bedrooms and a two-car garage. The system boundary includes the inputs and outputs of energy, materials, and emissions to air, soil, and water from extraction of raw materials though construction, maintenance, and occupancy. The house energy use was modeled using DOE-2.1E and the life cycle impact assessment was modeled using SimaPro.

The results show that for a given climate, the life cycle environmental impacts are similar for the wood and CMU houses. The most significant environmental impacts are not from construction materials but from the production of electricity and natural gas and the use of electricity and natural gas in the houses by the occupants.

REFERENCE

Marceau, Medgar L., and VanGeem, Martha G., *Comparison of the Life Cycle Assessments of a Concrete Masonry House and a Wood Frame House*, SN3042, Portland Cement Association, Skokie, Illinois, USA, 2008, 59 pages.

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ACRONYMS AND ABBREVIATIONS

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers

CMU concrete masonry unit

EDIP Environmental Design of Industrial Products (UMIP in Danish)

EPS Environmental Priority Strategies

ETH German abbreviation for Swiss Federal Technical University (Eidgenössische Technische Hochschule)

g gram

IECC International Energy Conservation Code

ISO International Organization for Standardization

kBtu thousand British thermal units (1×10^3 Btu)

kWh kilowatt-hour

GJ gigajoule (1×10^9 Joules) (1 GJ = 947817.1 Btu)

LCA life cycle assessment

LCI life cycle inventory analysis

LCIA life cycle impact assessment

MBtu million British thermal units (1×10^6 Btu)

MJ megajoule (1×10^6 Joules)

SI International system of units

SHGC solar heat gain coefficient

UMIP Danish abbreviation for Environmental Design of Industrial Products

Comparison of the Life Cycle Assessments of a Concrete Masonry House and a Wood Frame House

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INTRODUCTION

This report is an update of *Life Cycle Assessment of a Concrete Masonry House Compared to a Wood Frame House* (Marceau and VanGeem 2002). It presents the results of an assessment of the environmental attributes of concrete masonry construction compared to wood-framed construction. Each house has the same layout but is modeled with different exterior wall systems. The purpose of this update is to incorporate the most recent life cycle inventory (LCI) data on portland cement and portland cement concrete and the latest requirements in building energy conservation codes. This is a significant update because it reflects the increased stringency of newer energy codes. As the previous report shows, occupant use of energy, particularly electricity and natural gas for cooling and heating, represents the largest source of negative environmental impacts.

Life Cycle Assessment

Life cycle assessment (LCA) is a methodology for assessing the environmental aspects associated with a product over its life cycle—from raw material acquisition through production, use, and disposal (Goedkoop and others 2007). Performing an LCA is one of the possible methods of assessing a product's environmental aspects and the potential impacts it has on the natural environment. The International Organization for Standardization (ISO) has developed international standards that describe how to conduct an LCA. The ISO standards describe three phases of an LCA. The first phase is a life cycle inventory analysis, which consists of a compilation of the energy and material inputs and the emissions to air, land, and water associated with the manufacture of a product, operation of a process, or provision of a service. The second phase is an assessment of the potential social, economic, and environmental impacts associated with those inputs and emissions. The third phase is the interpretation of the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. These three phases are commonly referred to as (1) life cycle inventory analysis, (2) life cycle impact assessment, and (3) life cycle interpretation. The results of an LCA can be used to help choose among competing alternatives the alternative that has the most favorable attributes.

[1]Building Science Engineer, CTLGroup, 5400 Old Orchard Road, Skokie, Illinois 60077 USA, (847) 972-3154, MMarceau@CTLGroup.com, www.CTLGroup.com; Principal Engineer, CTLGroup, (847) 972-3156, MVanGeem@CTLGroup.com.

DEFINITION OF GOAL AND SCOPE

The LCA described in this report follows the guidelines in *International Standard ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines* (ISO 2006a). The previous version of this report referenced the 1997 edition of *International Standard ISO 14040, Environmental Management – Life Cycle Assessment – Principles and Framework*, and the 1999 edition of *International Standard ISO 14042, Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment*. However, updated editions of these standards are now referenced in *ISO 14044*.

Goal

The goal of this project is to compare the environmental impacts of a concrete masonry house to those of a wood frame house. To achieve this goal we use life cycle inventory data to conduct a life cycle assessment on two kinds of houses: one with concrete masonry unit (CMU) walls, the other with wood-frame walls. Since the largest source of negative environmental impacts in a house is from household use of energy, which is primarily a function of climate, the houses are modeled in five cities representing the range of climates in the US.

The reason for doing this work is to disseminate information on the LCAs of houses, which are based on the most complete and up-to-date life cycle inventory data from concrete and concrete products. The intended audience is building professionals who are interested in green buildings.

Scope

The scope of the LCA is defined by the function of a single-family house, the functional unit, and the system boundary.

Product Function. The function of a single-family house is to shelter the inhabitants from the environment and provide space for habitation.

Functional Unit. The functional unit, which is the basis for comparison, is defined in *International Standard ISO 14040, Environmental Management - Life Cycle Assessment - Principles and Framework* (ISO 2006b), as the quantified performance of a product system. In this work, the functional unit is a single-family house. The life of the house is assumed to be 100 years, and it includes maintenance and replacement of components as they wear out.

System Boundary. The system boundary is the interface between the functional unit and the environment. The system boundary in this work, shown in Figure 1, includes the inputs and outputs of energy and material from construction, occupancy, maintenance, demolition, and disposal. Transporting materials to and from the house is also included. This is called a *second order* system boundary because in addition to material and energy flows, it includes operations. Occupancy consists of household use of electricity and natural gas. Electricity is used for fans, lights, cooling (air conditioner), appliances, and plug loads. Natural gas is used for heating (furnace) and domestic hot water. Maintenance consists of the materials used to repair and replace items that normally wear out. The system boundary excludes capital goods (such as existing infrastructure), human labor, impacts caused by people, and waste treatment after disposal. An LCA of buildings typically does not include measures of disaster resistance, occupant comfort, or occupant productivity. The ISO standards indicate that inputs to a product or process do not need to be included in an LCI if (1) they do not represent a significant fraction of the total mass of processed materials or product, (2) they do not contribute significantly to a toxic emission, and (3) they do not represent a significant amount of energy.

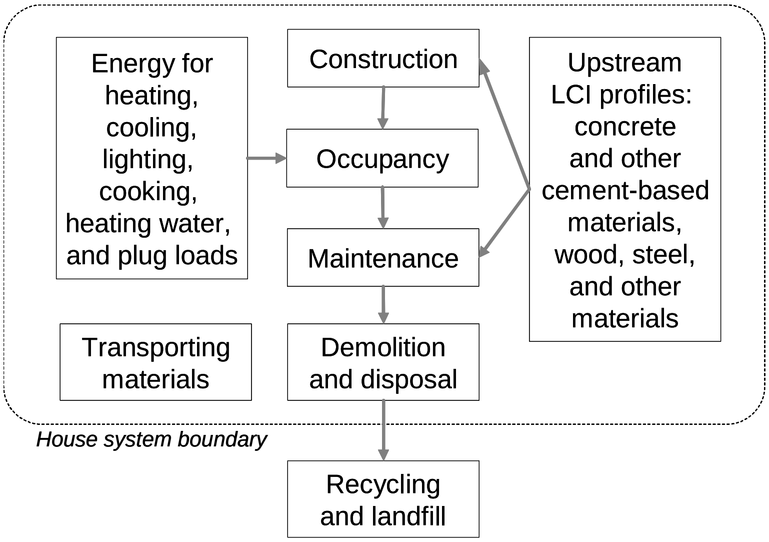

Figure 1. The system boundary (dashed line) defines the limits of the life cycle assessment.

Critical Review. The previous version of this report was reviewed by the Technical Research Centre of Finland (VTT, Valtion Teknillinen Tutkimuskeskus). The reviewers found that it was a careful study on the environmental aspects of CMU and wood frame houses. They concluded that the report "properly uses the life cycle assessment approach in accordance with the framework described in the *ISO 14040* and *ISO 14042* standards" (Häkkinen and Holt, 2002). Both *ISO 14040* and *ISO 14042* are now referenced in *ISO 14044*. It is our opinion that an updated critical review is not required because the present version includes the same methodology as the previous version with the addition of more recent data, more specific data, and more complete data.

Data Quality. From all the available data that could be used, preference is given to the most recent product-specific data for North America representing an average level of technology. When North American data are not available, European data are used.

HOUSE DESCRIPTION

The houses were designed by CTLGroup. The designs are based on typical houses currently built in the US. Each house is a two-story single-family building with four bedrooms, 2.7-m (9-ft) ceilings, a two-story foyer and family room, and an attached two-car garage. Both the wood frame and CMU houses have the same layout. Each house has 228 square meters (2450 square feet) of living space, which is similar to the 2005 U.S. average of 226 square meters (2434 square feet) (NAHB 2007). Drawings of the house are shown in Appendix A. The floor plans are shown in Figures A-1 and A-2 and the elevations are shown in Figures A-3 to A-6. Typical wall sections are shown in Figures A-7 and A-8.

Climate

Since the energy use of a building depends on local climate, the houses are modeled in several different climates. Five cities that represent the range of climates in the US were chosen: Lake Charles, Louisiana; Tucson, Arizona; St. Louis, Missouri; Denver, Colorado; and Minneapolis, Minnesota. The locations selected are those often used by other energy analysts when estimating national energy use in buildings. The cities and the climate zone numbers are:

- Lake Charles, Louisiana —a hot – humid climate (Zone 2A).
- Tucson, Arizona—a hot – dry climate with large daily temperature swings (Zone 2B).
- St. Louis, Missouri —a mixed – humid climate (Zone 4A).
- Denver, Colorado—a cold – dry climate (Zone 5B).
- Minneapolis, Minnesota—a cold – humid climate (Zone 6).

The houses are designed to meet the requirements of the *2006 International Energy Conservation Code* (*IECC* 2006) in all locations. The IECC is the most widely used residential energy code in the US. Household energy use is modeled using whole-building energy simulation software. The energy modeling is described in the section, “Whole-Building Energy Use”.

Building Envelope Requirements

The *2006 IECC* requirements for fenestration and insulation are presented in Table 1 for the five cities where the houses are modeled. U-factor and solar heat gain coefficients (SHGC) requirements are maximums, whereas RSI-values (R-values) are minimums. U-factor is a measure of thermal conductance and generally represents the overall rate of heat loss of a given assembly, whereas R-value is a measure of thermal resistance and generally represents the thermal resistance of a given thickness of material. For ease of compliance and enforcement, the *2006 IECC* provides requirements for the added R-value of insulation between framing members. The *2006 IECC* also presents equivalent U-factors which include the thermal resistance of the entire assembly. These are presented in Table 2. Compliance may be demonstrated using either the values from Table 1 or the U-factors from Table 2. U-factor is expressed in SI units as $W/(m^2 \cdot K)$ and U.S. customary units as $Btu/(h \cdot ft^2 \cdot °F)$. R-value is expressed in SI units of $(m^2 \cdot K)/W$ and U.S. customary units of $(h \cdot ft^2 \cdot °F)/Btu$.

Table 1a. International Energy Conservation Code Insulation and Fenestration Requirements* (SI Units)

Climate zone	City	Fenestration		Ceiling RSI-value	Wood frame wall RSI-value	Mass wall RSI-value	Slab RSI-value & depth
		U-factor	SHGC				
2	Lake Charles, Tucson	4.3	0.40	5.3	2.3	0.7	0
4 except Marine	St. Louis	2.4	NR**	6.7	2.3	0.9	1.8, 0.6 m††
5 and Marine 4	Denver	2.0	NR**	6.7	3.3 or 2.3+0.9†	2.3	1.8, 0.6 m††
6	Minneapolis	2.0	NR**	8.6	3.3 or 2.3+0.9†	2.6	1.8, 1.2 m††

*Adapted from IECC (2006) Table 401.1.1. U-factor in W/(m^2·K) and RSI-value in (m^2·K)/W.
** "NR" means no requirement.
† "2.3+0.9" means RSI-2.3 cavity insulation plus R-0.9 insulated sheathing.
†† "1.8, 0.6 m" means RSI-1.8 insulation 0.6 m deep.

Table 1b. International Energy Conservation Code Insulation and Fenestration Requirements* (U.S. Customary Units)

Climate zone	City	Fenestration		Ceiling R-value	Wood frame wall R-value	Mass wall R-value	Slab R-value & depth
		U-factor	SHGC				
2	Lake Charles, Tucson	0.75	0.40	30	13	4	0
4 except Marine	St. Louis	0.40	NR**	38	13	5	10, 2 ft††
5 and Marine 4	Denver	0.35	NR**	38	19 or 13+5†	13	10, 2 ft††
6	Minneapolis	0.35	NR**	49	19 or 13+5†	15	10, 4 ft††

*Adapted from IECC (2006) Table 401.1.1. U-factor in Btu/(h·ft^2·°F) and R-value in (h·ft^2·°F)/Btu.
** "NR" means no requirement.
† "13+5" means R-13 cavity insulation plus R-5 insulated sheathing.
†† "10, 2 ft" means R-10 insulation 2 ft deep.

Table 2a. International Energy Conservation Code Equivalent U-Factor Requirements* (SI Units)

Climate zone	City	Fenestration	Ceiling	Wood frame wall	Mass wall
2	Lake Charles, Tucson	4.3	0.20	0.47	0.937
4 except Marine	St. Louis	2.3	0.17	0.47	0.801
5 and Marine 4	Denver	2.0	0.17	0.34	0.466
6	Minneapolis	2.0	0.15	0.34	0.341

*Adapted from IECC (2006) Table 402.1.3. U-factor in W/(m^2·K). There is no U-factor equivalent for slab perimeter insulation.

Table 2b. International Energy Conservation Code Equivalent U-Factor Requirements* (U.S. Customary Units)

Climate zone	City	Fenestration	Ceiling	Wood frame wall	Mass wall
2	Lake Charles, Tucson	0.75	0.035	0.082	0.165
4 except Marine	St. Louis	0.40	0.030	0.082	0.141
5 and Marine 4	Denver	0.35	0.030	0.060	0.082
6	Minneapolis	0.35	0.026	0.060	0.060

*Adapted from IECC (2006) Table 402.1.3. U-factor in Btu/(h·ft^2·°F). There is no U-factor equivalent for slab perimeter insulation.

Building Envelopes As-Modeled

The building envelope (roofs, exterior walls, windows, and slab-on-ground floors) in each location meets the requirements of the *2006 IECC* using typical building materials and typical building practices. The fenestration and insulation used in the modeling are presented in Table 3. The as-modeled building envelope U-factors are shown in Table 4. The amount by which the as-modeled values differ from the *2006 IECC* criteria is shown in Table 5.

Table 3a. Fenestration and Insulation As-Modeled* (SI Units)

Climate zone	City	Fenestration		Ceiling RSI-value	Wood frame wall RSI-value	Mass wall (CMU) RSI-value	Slab RSI-value & depth
		U-factor	SHGC				
2	Lake Charles, Tucson	3.3	0.30	5.3	2.3	1.4	0
4 except Marine	St. Louis	2.1	0.64	6.7	2.3	2.3	1.8, 0.6 m†
5 and Marine 4	Denver	2.0	0.56	6.7	2.3+0.9**	2.3	1.8, 0.6 m†
6	Minneapolis	2.0	0.56	8.6	2.3+0.9**	2.6	1.8, 1.2 m†

*U-factor in W/(m^2·K) and RSI-value in (m^2·K)/W.
** "2.3+0.9" means RSI-2.3 cavity insulation plus R-0.9 insulated sheathing.
† "1.8, 0.6 m" means RSI-1.8 insulation 0.6 m deep.

Table 3b. Fenestration and Insulation As-Modeled* (U.S. Customary Units)

Climate zone	City	Fenestration		Ceiling R-value	Wood frame wall R-value	Mass Wall (CMU) R-value	Slab R-value & depth
		U-factor	SHGC				
2	Lake Charles, Tucson	0.57	0.30	30	13	8	0
4 except Marine	St. Louis	0.37	0.64	38	13	13	10, 2 ft†
5 and Marine 4	Denver	0.35	0.56	38	13+5**	13	10, 2 ft†
6	Minneapolis	0.35	0.56	49	13+5**	15	10, 4 ft†

*U-factor in Btu/(h·ft^2·°F) and R-value in (h·ft^2·°F)/Btu.
** "13+5" means R-13 cavity insulation plus R-5 insulated sheathing.
† "10, 2 ft" means R-10 insulation 2 ft deep.

Table 4a. Building Envelope U-Factors As-Modeled* (SI Units)

Climate zone	City	Fenestration	Ceiling	Wood frame wall	Mass wall (CMU)
2	Lake Charles, Tucson	3.3	0.18	0.49	0.68
4 except Marine	St. Louis	2.1	0.15	0.49	0.46
5 and Marine 4	Denver	2.0	0.15	0.33	0.46
6	Minneapolis	2.0	0.12	0.33	0.43

*U-factor in W/(m^2·K). U-factors include an interior air film of 0.39 m^2·K/W. There is no U-factor equivalent for slab perimeter insulation.

Table 4b. Building Envelope U-Factors As-Modeled* (U.S. Customary Units)

Climate zone	City	Fenestration	Ceiling	Wood frame wall	Mass wall (CMU)
2	Lake Charles, Tucson	0.57	0.032	0.086	0.12
4 except Marine	St. Louis	0.37	0.026	0.086	0.081
5 and Marine 4	Denver	0.35	0.026	0.058	0.081
6	Minneapolis	0.35	0.021	0.058	0.075

*U-factor in Btu/(h·ft^2·°F). U-factors include an interior air film of 0.68 h·ft^2·°F/Btu. There is no U-factor equivalent for slab perimeter insulation.

Table 5. Amount by Which As-Modeled Building Envelope Components Exceed International Energy Conservation Code Requirements

Climate zone	City	Fenestration	Ceiling	Wood frame wall	Mass wall (CMU)
2	Lake Charles, Tucson	24%	0%	0%	100%
4 except Marine	St. Louis	8%	0%	0%	160%
5 and Marine 4	Denver	0%	0%	0%	0
6	Minneapolis	0%	0%	0%	0

Windows. Windows are aluminum framed with thermal breaks and double panes. They are primarily located on the front and back façades, and the overall window-to-exterior wall ratio is 16%.

Roofs and Ceilings. Roofs and ceilings are wood-frame construction. The ceilings have RSI-5.3 (R-30), RSI-6.7 (R-38), or RSI 8.6 (R-49) fiberglass batt insulation as required in the *2006 IECC*, depending on climate. The U-factor includes RSI-1.0 (R-0.56) for 16-mm (0.625-in.) gypsum board and RSI-0.11 (R-0.61) for interior air film heat flow up. Roofs are covered with medium-colored asphalt shingles.

Exterior Walls. The exterior walls of the wood-frame houses with RSI-2.3 (R-13) insulation consist of medium-colored aluminum siding, 12-mm (½-in.) wood sheathing, RSI-2.3 (R-13) fiberglass batt insulation between 2×4 wood studs 400 mm (16 in.) on center, and 12-mm (½-in.)

painted gypsum board. This is typical of wood-framed construction in the US. The exterior walls of the wood-frame houses with RSI-2.3+0.9 (R-13+5) insulation is the same as above but with RSI-0.9 (R-5) continuous insulation utilized in-place of wood sheathing. The calculated U-factor of the as-modeled assembly shown in the tables includes an interior air film of 0.12 $m^2 \cdot K/W$ (0.68 $h \cdot ft^2 \cdot °F/Btu$).

The concrete masonry unit (CMU) walls consist of partially grouted normal-weight CMUs, interior wood furring spaced 400 mm (16 in.) on center, gypsum wallboard on the inside surface, and stucco on the outside surface. Further, in Lake Charles and Tucson there is RSI-1.4 (R-8) insulation between the wood furring, in Washington (DC), St. Louis, and Denver there is RSI-2.3 (R-13) insulation, and in Minneapolis there is RSI-2.6 (R-15) insulation.

Interior Walls and Floors. Interior walls and floors are wood-framed and uninsulated. Second story floors are covered with a combination of carpet and tile (bathrooms).

Slab Foundation. In all cities, the houses are slab-on-ground construction. The slab-on-ground floor consists of 150-mm (6 in.) thick normal-weight concrete cast on soil and covered with a combination of carpet, linoleum (kitchen and laundry room), and tile (bathrooms). The slabs are insulated according to the requirements in the *2006 IECC*.

Occupant Behavior and Other Performance Characteristics

Occupant behavior is one of the most important factors affecting energy use in a house. Therefore, to create realistic models of the house, occupant behavior and other performance characteristics are assumed to be the same for all houses. This ensures that comparisons between houses within a given climate are fair and valid. Thus, the houses have identical air-infiltration rates and the house systems have identical controls, schedules, and performance characteristics for lighting, heating, air conditioning, and water heating.

Heating, Ventilating, and Air-Conditioning. The heating, ventilating, and air-conditioning (HVAC) system consists of a natural gas high-efficiency forced-air furnace and an electric high-efficiency central air conditioner. The efficiencies of the HVAC components are assumed to be identical in all cities. The heating thermal efficiency is 0.8 (that is, 80% efficient), and the cooling energy efficiency ratio is 0.9 including fan efficiency (that is, 90% efficient). HVAC equipment is sized for each location and for the peak heating and cooling loads of a particular house. Generally wood houses require larger HVAC equipment. The HVAC system is controlled by a residential thermostat located in the family room. The heating set-point temperature is 21°C (70°F), and the cooling set-point temperature is 24°C (75°F).

Domestic Hot Water. Hot water is supplied by a natural gas water heater, which has a peak utilization of 9.5 liters/minute (2.5 gallons/minute). The hot water load-profile was taken from *ASHRAE Standard 90.2-1993* (ASHRAE 1993).

Other Energy Use. Occupant use of energy, other than for heating and cooling, is based on the daily internal heat gain profile in *ASHRAE Standard 90.2-2004, Energy Efficient Design of Low-Rise Residential Buildings* (ASHRAE 2004, Table 8.8.1). It is approximately 7300 kWh per year.

Air Infiltration. The fresh air ventilation rate is based on the minimum requirement to maintain acceptable indoor air quality in *ASHRAE Standard 62.2-2003, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings* (ASHRAE 2003). Assuming a family of four, it is equivalent to an air infiltration rate of 7 liters/minute per m^2 of conditioned floor area (0.02 cu ft/minute per sq ft).

Designed Life. The life of the house is assumed to be 100 years. The replacement schedules for various building components are shown in Table 6.

Table 6. House Component Replacement Schedules

House component	Replacement schedule (years)
Siding, air barrier, and exterior fixtures	33.3
Latex and silicone caulking	10
Paint, exterior	5
Doors and windows	33.3
Roofing*	20 and 40
Gable and ridge vents	33.3
Bathroom fixtures	25
Bathroom tiles and backer board	25
Paint, interior	10
Carpet and pad	10
Resilient flooring, linoleum	10
Bathroom furniture (toilet, sink, etc.)	25
Garbage disposal	20
Furnace	20
Air conditioner	20
Interior and exterior luminaries	33.3
Water heater	20
Large appliances	15
Manufactured fireplace	50
Kitchen and bathroom casework	25
Kitchen counter tops	25

*A new layer of shingles is added every 20 years, and every 40 years the existing layers of felt and shingles are replaced with a new layer of felt and shingles.

Whole-Building Energy Use

Whole-building energy simulation software is used to model household energy use. The software is *HVAC Sizing for Concrete Homes, Version 3.0* (PCA 2005). This software uses the U.S. Department of Energy DOE-2.1E hourly simulation tool as the calculation engine (Winkelmann and others 1993). It is used to simulate hourly energy use and peak demand over a one-year period. Programs that model hourly energy use are more accurate than other methods, especially for buildings with thermally massive exterior walls, such as concrete wall systems.

Heating and cooling load vary with solar orientation, so the houses are modeled four times: once for each orientation of the front façade facing the four cardinal directions (north, south, east, and west). Then the energy for heating, cooling, hot water, and occupant use is averaged to obtain energy use that is independent of building orientation. The annual energy use is presented in Table 7. Actual energy use will vary depending on climate, building type, use and occupancy, orientation, actual building materials, and fenestration amount and type. Although energy simulation is not an accurate *predictor* of energy use, it is a suitable tool for comparing and evaluating *different design alternatives* when the factors that affect energy use have been isolated. In each of the five climates, the CMU houses have similar household energy use as the wood frame houses (the difference is within 1 to 6%, depending on climate), even though the added R-values for the CMU house are generally less than those for the wood frame house (Table 3).

Table 7. Annual Whole-Building Energy Use

Location	House	Annual operating data					Energy savings*
		Electricity		Natural gas		Total	
		GJ	kWh	GJ	Therms	GJ	
Lake Charles	Wood frame	52.6	14,608	87.2	827	139.8	…
	CMU	53.6	14,882	87.2	827	140.8	-1%
Tucson	Wood frame	58.3	16,208	81.1	769	139.5	…
	CMU	58.1	16,139	73.6	698	131.7	6%
St. Louis	Wood frame	54.9	15,256	134.6	1,276	189.5	…
	CMU	53.7	14,923	125.7	1,191	179.4	5%
Denver	Wood frame	46.1	12,793	128.4	1,217	174.5	…
	CMU	44.0	12,234	132.6	1,257	176.6	-1%
Minneapolis	Wood frame	43.9	12,188	167.2	1,585	211.1	…
	CMU	43.3	12,029	177.3	1,681	220.6	-5%

*Energy savings is based on the wood frame house. A positive number means the CMU house uses less energy than the wood frame house.

The system capacity required for heating, ventilating, and air-conditioning is similar for the CMU and wood frame houses. Table 8 shows the maximum 1-hour HVAC system loads as determined by the energy simulation software. The thermal mass of the CMU house moderates temperature swings and peaks loads, and this results in similar HVAC system requirements even though the CMU house generally has less added insulation.

Table 8. Maximum HVAC System Loads

Location	House	Maximum HVAC system loads			
		Heating		Cooling	
		kW	kBtu/h	kW	kBtu/h
Lake Charles	Wood frame	7.0	24	9.8	34
	CMU	7.3	25	8.9	30
Tucson	Wood frame	6.4	22	9.9	34
	CMU	6.3	22	9.3	32
St. Louis	Wood frame	9.6	33	13.4	46
	CMU	8.6	29	12.2	42
Denver	Wood frame	8.6	29	9.9	34
	CMU	8.7	30	8.9	31
Minneapolis	Wood frame	9.9	34	10.4	35
	CMU	10.3	35	9.7	33

Natural gas fired high-efficiency forced-air furnaces are typically available in 20 kBtu/hr capacity increments (equivalent to 5.9 kW) and high-efficiency central air conditioners are typically available in 6 to 12 kBtu/hr (½ to 1 ton) capacity increments (equivalent to 1.8 to 3.5 kW). Because HVAC systems are typically oversized (the installed capacity is the required capacity rounded to the next larger available capacity), actual installed system capacity savings will be different.

SIMAPRO LIFE CYCLE ASSESSMENT SOFTWARE

SimaPro is a software tool for compiling life cycle inventory data and for modeling the environmental impacts of materials and processes. There are several LCA software tools that can be used to perform life cycle impact assessment, but we have chosen to use SimaPro because it contains many extensive databases of materials and processes, and because it contains the most extensive set of life cycle impact assessment methods of all the tools we have surveyed.

LIFE CYCLE INVENTORY ANALYSIS

Life cycle inventory analysis (LCI) is the “phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 2006b). The LCI of the house comprises the energy and material inputs and outputs of all the activities and materials included in the system boundary shown in Figure 1.

House Materials Inputs

The material inputs to construction and maintenance are calculated from the house plans and elevations and from the house component replacement schedule. Table 9 shows the material inputs over the 100-year life of the house in each city. Each of these materials has its own upstream LCI profile. SimaPro is used both as a source of upstream LCI profiles and as a modeling environment in which to compile the LCI data.

Concrete and Other Cement-Based Materials. The upstream LCI profiles of concrete and other cement-based materials are imported into SimaPro from *Life Cycle Inventory of Portland Cement Concrete* (Marceau and others 2007). The ready mixed concrete is 20-MPa (3,000-psi) concrete with 25% fly ash substitution for portland cement. Fly ash, which is a pre-consumer waste, is often used to replace a portion of the portland cement in concrete. The concrete masonry mix also contains 25% fly ash. Mix proportions are presented in Table 10. Concrete mix proportions vary depending on supplier, available materials, and material properties. More information on the effects of concrete mix proportions on LCI results is given in the referenced report.

The CMU house has two to three times as much cement-based material as the wood frame house because, in addition to the foundation, the exterior walls are also concrete. The houses in the cooler climates also have more concrete because they have deeper concrete foundations.

All Other Building Materials. The upstream LCI profiles of all other material come from one or more of the materials databases in SimaPro. When a particular building material was not available in any of the databases, or where the available material did not meet the stated data quality requirements, an LCI of the building material was assembled with the available materials and processes. The source of LCI data for all building materials is shown in Table 11.

Both houses contain similar amounts of wood (the difference is less than 15%) because in both houses the roof, interior walls, second story floor, and windows and doors are framed with wood.

Almost all materials in the houses are included in the LCI. The materials that are not represented in the available databases constitute a minor fraction of the mass of a house, and they represent components that are used in similar amounts in the two houses. They are carpets, underpads, appliances, sealants, and miscellaneous polymers. The mass of materials excluded is shown in Table 12.

Table 9a. House Materials List (SI Units)*

	Wood frame house					Normal weight CMU house				
Material, kg	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Ready-mixed concrete**	70,661	76,166	92,682	109,198	136,725	70,661	76,166	92,682	109,198	136,725
CMUs, normal weight	0	0	0	0	0	63,504	63,504	63,504	63,504	63,504
Cement-based material, other	1,545	1,545	1,545	1,545	1,545	65,126	65,126	65,126	65,126	65,126
fiber-cement backer board	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545
mortar	0	0	0	0	0	35,889	35,889	35,889	35,889	35,889
grout	0	0	0	0	0	3,929	3,929	3,929	3,929	3,929
stucco	0	0	0	0	0	23,763	23,763	23,763	23,763	23,763
Metal	3,453	3,523	3,736	3,949	4,304	4,246	4,317	4,529	4,742	5,097
aluminum	849	849	849	849	849	315	315	315	315	315
copper	67	67	67	67	67	67	67	67	67	67
galvanized steel	310	310	310	310	310	310	310	310	310	310
sheet metal	372	372	372	372	372	372	372	372	372	372
steel	1,854	1,925	2,137	2,350	2,705	3,181	3,252	3,465	3,678	4,032
Wood	20,400	20,400	20,400	20,400	20,400	19,450	19,450	19,450	19,450	19,450
framing	10,753	10,753	10,753	10,753	10,753	10,099	10,099	10,099	10,099	10,099
treated	676	676	676	676	676	2,001	2,001	2,001	2,001	2,001
plywood	5,040	5,040	5,040	5,040	5,040	4,446	4,446	4,446	4,446	4,446
sheathing	1,027	1,027	1,027	1,027	1,027	0	0	0	0	0
miscellaneous	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904
Gypsum wallboard	8,896	8,896	8,896	8,896	8,896	8,035	8,035	8,035	8,035	8,035
Insulation, polystyrene	0	0	120	362	481	0	0	120	120	239
Insulation, fiberglass	543	543	627	627	741	393	393	509	627	775
Polymers and linoleum	10,243	10,243	10,243	10,243	10,243	10,072	10,072	10,072	10,072	10,072
carpet and pad	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421
linoleum	364	364	364	364	364	364	364	364	364	364
paint	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690
polyolefin (polyethylene)	22	22	22	22	22	0	0	0	0	0
polyvinyl chloride (PVC)	430	430	430	430	430	430	430	430	430	430
sealant	299	299	299	299	299	150	150	150	150	150
general	16	16	16	16	16	16	16	16	16	16
Roofing materials	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827
Windows	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128
Ceramic tile	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641
Lighting products	577	577	577	577	577	577	577	577	577	577
Electrical wire	111	111	111	111	111	111	111	111	111	111
Appliances and HVAC	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470
Total (rounded)	**134,500**	**140,100**	**157,000**	**174,000**	**202,100**	**260,200**	**265,800**	**282,800**	**299,600**	**327,800**

*Includes items replaced during the 100-year life.

**More material is used in colder climates because foundations are deeper.

Table 9b. House Materials List (U.S. Customary Units)*

	Wood frame house					Normal weight CMU house				
Material, lb	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**	**Lake Charles**	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Ready-mixed concrete**	155,780	167,918	204,329	240,741	301,426	155,780	167,918	204,329	240,741	301,426
CMUs, normal weight	0	0	0	0	0	140,001	140,001	140,001	140,001	140,001
Cement-based material, other	3,406	3,406	3,406	3,406	3,406	143,578	143,578	143,578	143,578	143,578
fiber-cement backer board	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406
mortar	0	0	0	0	0	79,121	79,121	79,121	79,121	79,121
grout	0	0	0	0	0	8,663	8,663	8,663	8,663	8,663
stucco	0	0	0	0	0	52,388	52,388	52,388	52,388	52,388
Metal	7,611	7,768	8,237	8,706	9,488	9,360	9,517	9,986	10,455	11,236
aluminum	1,873	1,873	1,873	1,873	1,873	694	694	694	694	694
copper	147	147	147	147	147	147	147	147	147	147
galvanized steel	684	684	684	684	684	684	684	684	684	684
sheet metal	821	821	821	821	821	821	821	821	821	821
steel	4,086	4,243	4,712	5,181	5,963	7,013	7,170	7,639	8,108	8,890
Wood	44,975	44,975	44,975	44,975	44,975	42,881	42,881	42,881	42,881	42,881
framing	23,707	23,707	23,707	23,707	23,707	22,265	22,265	22,265	22,265	22,265
treated	1,489	1,489	1,489	1,489	1,489	4,412	4,412	4,412	4,412	4,412
plywood	11,111	11,111	11,111	11,111	11,111	9,802	9,802	9,802	9,802	9,802
sheathing	2,265	2,265	2,265	2,265	2,265	0	0	0	0	0
miscellaneous	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402
Gypsum wallboard	19,612	19,612	19,612	19,612	19,612	17,715	17,715	17,715	17,715	17,715
Insulation, polystyrene	0	0	264	797	1,060	0	0	264	264	527
Insulation, fiberglass	1,198	1,198	1,382	1,382	1,634	866	866	1,123	1,382	1,708
Polymers and linoleum	22,583	22,583	22,583	22,583	22,583	22,204	22,204	22,204	22,204	22,204
carpet and pad	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156
linoleum	803	803	803	803	803	803	803	803	803	803
paint	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931
polyolefin (polyethylene)	49	49	49	49	49	0	0	0	0	0
polyvinyl chloride (PVC)	949	949	949	949	949	949	949	949	949	949
sealant	659	659	659	659	659	330	330	330	330	330
general	35	35	35	35	35	35	35	35	35	35
Roofing materials	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847
Windows	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896
Ceramic tile	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026
Lighting products	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Electrical wire	245	245	245	245	245	245	245	245	245	245
Appliances and HVAC	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058
Total (rounded)	**296,500**	**308,800**	**346,100**	**383,500**	**445,500**	**573,700**	**586,000**	**623,400**	**660,600**	**722,600**

*Includes items replaced during the 100-year life.

**More material is used in colder climates because foundations are deeper.

Table 10a. Mix Designs* for Concrete and Other Cement-Based Materials (SI Units)

Mix constituent, kg/m^3	20-MPa ready mixed concrete, 25% fly ash	Concrete masonry**, 25% fly ash	Mortar	Grout, 15% fly ash	Stucco
Portland cement	167	155	261	380	593
Fly ash	56	52	0	65	0
Limestone	0	0	172	0	0
Water	141	142	208	243	77
Coarse aggregate	1127	619	0	0	0
Fine aggregate	831	1414	1365	1305	1721
Total	**2322**	**2382**	**2006**	**1993**	**2391**

*Mix designs vary; these ones have been chosen because they are representative of residential applications.
**Yield is 131 CMU/m^3.

Table 10b. Mix Designs* for Concrete and Other Cement-Based Materials (U.S. Customary Units)

Mix constituent, lb/yd^3	3000-psi ready mixed concrete, 25% fly ash	Concrete masonry**, 25% fly ash	Mortar	Grout, 15% fly ash	Stucco
Portland cement	282	262	440	640	1000
Fly ash	94	88	0	110	0
Limestone	0	0	290	0	0
Water	237	240	350	410	130
Coarse aggregate	1900	1043	0	0	0
Fine aggregate	1400	2384	2300	2200	2900
Total	**3913**	**4017**	**3380**	**3360**	**4030**

*Mix designs vary; these ones have been chosen because they are representative of residential applications.
**Yield is 100 CMU/yd^3.

Table 11. Sources of Upstream LCI Data

Material and energy	Database(s)	Reference(s)
Aluminum	Franklin US LCI	Norris 2003
Cement-based materials	PCA	Marceau and others 2006 and 2007
Ceramic tile	Ecoinvent IDEMAT 2001	Frischknecht and others 2004 Remmerswaal 2001
Copper	Ecoinvent ETH-ESU 96	Frischknecht and others 2004 Frischknecht and Jungbluth 2004
Electrical wire	Franklin US LCI Eco-Invent IDEMAT 2001 ETH-ESU 96	Norris 2003 Frischknecht and others 2004 Remmerswaal 2001 Frischknecht and Jungbluth 2004
Expanded polystyrene insulation	Franklin US LCI	Norris 2003
Fiberglass insulation	Ecoinvent	Frischknecht and others 2004
Gypsum wall board	Ecoinvent	Frischknecht and others 2004
Lights	ETH-ESU 96	Frischknecht and Jungbluth 2004
Linoleum	IDEMAT 2001	Remmerswaal 2001
Paint	ETH-ESU 96	Frischknecht and Jungbluth 2004
Particle board	Ecoinvent	Frischknecht and others 2004
Polyester fabric	IDEMAT 2001	Remmerswaal 2001
Polyvinyl chloride (PVC)	INDUSTRY DATA	APME 2000
Roofing	Franklin US LCI IDEMAT	Norris 2003 Remmerswaal 2001
Steel: sheets and galvanized	Franklin US LCI	Norris 2003
Windows	Franklin US LCI Ecoinvent IDEMAT 2001 ETH-ESU 96	Norris 2003 Frischknecht and others 2004 Remmerswaal 2001 Frischknecht and Jungbluth 2004
Wood: framing, treated, plywood, sheathing	ETH-ESU 96	Frischknecht and Jungbluth 2004
Diesel hydraulic excavator	Ecoinvent	Frischknecht and others 2004
Diesel tractor-trailer transportation	Franklin US LCI	Norris 2003
Electricity, U.S. average	Franklin US LCI	Norris 2003
Natural gas combustion in residential furnace	Ecoinvent	Frischknecht and others 2004
Concrete and cement plant fuels	Franklin US LCI Ecoinvent	Norris 2003 Frischknecht and others 2004

Table 12. Materials Excluded from the LCA because of Insufficient Data

Material	Wood Amount		CMU Amount	
	kg	lb	kg	lb
Floor carpet and under-pad	6,400	14,200	6,400	14,200
Appliances and HVAC	5,500	12,000	5,500	12,000
Sealant	300	660	300	660
Miscellaneous polymers	20	40	20	40
Subtotal	12,000	27,000	12,000	27,000
Total mass of house (average)	161,000	356,000	287,000	633,000
Total mass excluded from LCA	7%		4%	

House Energy Inputs

Construction. Apart from human labor, most of the energy used for on-site construction is in excavating the foundation. Depending on the foundation depth, between 110 to 340 m^3 (4000 to 12000 ft^3) of soil is excavated. Assuming a typical hydraulic excavator, the embodied energy of this process is 900 to 2700 MJ (850 to 2600 kBtu) (Frischknecht and others 2004). This represents approximately 1% of the *annual* household energy use and approximately 0.01% of the *life cycle* household energy use.

Occupancy. Life cycle household energy use is the annual energy use (see Table 7) multiplied by 100.

Demolition and disposal. The energy for demolition and disposal is assumed to be less than that used in excavation because it takes less energy to demolish a house than to build it. As such, demolition and disposal would be less than 0.01% of the *life cycle* household energy use. Therefore, no significant error is introduced by omitting this energy.

Transportation. Transportation includes transporting the mass of all materials to the house throughout the life of the house, and transporting the mass of all material to a landfill at the end of life. All material is assumed to be transported by tractor-trailers using diesel fuel and traveling on paved roads. The average haul distance is assumed to be 80 kilometers (50 miles) for all material. The energy used in return trips (when an empty truck returns to its home base) is not included because this type of vehicle usually makes deliveries at more than one job site per trip. Therefore, the transportation energy is overestimated. However, depending on house style, the embodied energy of this process ranges from 22 to 54 GJ (21 to 51 MBtu) (Norris 2003), which is approximately 25% of the *annual* household energy use and approximately 0.25% of the *life cycle* household energy use.

LIFE CYCLE IMPACT ASSESSMENT

Life cycle impact assessment (LCIA) is the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life of the product" (ISO 2006b). LCIA consists of category definition, classification, and characterization. Category definition consists of identifying which impact categories are relevant for the product being studied. Classification consists of grouping related substances into impact categories. For example, the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) contribute to global warming; as a result, they can be grouped together in an impact category called climate change.

According to *ISO 14044*, the mandatory step in life cycle impact assessment is characterization. In characterization, weighting factors are assigned according to a substance's relative contribution to the impact category. For example, in terms of global warming potential, one pound of methane is 20 times more potent than one pound of CO_2, and one pound of N_2O is 320 times more potent than one pound of CO_2. Therefore, in assessing the potential for global warming, CO_2 is assigned a weighting factor of 1, CH_4 a factor of 20, and N_2O a factor of 320. It is important to remember that there is no scientific basis for comparing across impact categories.

According to *ISO 14042,* life cycle impact assessment is not intended to identify, measure, or predict actual impacts or estimate threshold limits, or measure margins of safety. The methodology is still being developed, and there is no general and widespread practice of life cycle impact assessment at this time or an agreement on specific methodologies. Therefore, several of the available methods were used to measure the life cycle impact assessment. The methods chosen are Eco-Indicator 99 (Dutch/Swiss), EDIP/UMIP 97 (Danish), and EPS 2000 (Swedish). Furthermore, three different weighting sets in Eco-Indicator 99 were used.

The Eco-Indicator 99 method is a damage-oriented approach, which is based on how a panel of experts weighted the different types of damage caused by the impact categories. The three versions of Eco-Indicator 99 reflect the subjective uncertainty inherent in LCA. Each one takes a different perspective on how to consider the potential damage from a particular substance. The egalitarian perspective takes an extremely long-term look at substances if there is any indication that they have some effect. The hierarchic perspective takes a long-term look at all substances if there is consensus regarding their effect. The individualist perspective takes a short-term look (100 years or less) at substances if there is complete proof regarding their effect.

The EDIP/UMIP 97 method is based on normalizing values to person-equivalents in 1990 and weighting factors are equivalent to politically-set target-emissions per person in 2000.

The EPS 2000 method was designed as a tool for a company's internal product development process, and the weighting factors are based on a willingness to pay to avoid change.

A listing of the impact categories in each method is shown in Table 13. A complete description of the category definitions, category endpoint, classification methods, and characterization factors for each of the three methods is too voluminous to be reproduced in this report. Please refer to Appendices B for a summary of each method and further references.

Table 13. Impact Categories for Three Life Cycle Impact Assessment Methods

Eco-Indicator 99	EDIP/UMIP 97	EPS 2000
Carcinogens	Global warming potential (GWP 100)	Life expectancy
Respiratory organics	Ozone depletion	Severe morbidity
Respiratory inorganics	Acidification	Morbidity
Climate change	Eutrophication	Severe nuisance
Radiation	Photochemical smog	Nuisance
Ozone layer	Ecotoxicity water, chronic	Crop growth capacity
Ecotoxicity	Ecotoxicity water, acute	Wood growth capacity
Acidification/eutrophication	Ecotoxicity soil, chronic	Fish and meat production
Land use	Human toxicity, air	Soil acidification
Minerals	Human toxicity, water	Production capacity of irrigation water
Fossil fuels	Human toxicity, soil	Production capacity of drinking water
	Bulk waste	Depletion of reserves
	Hazardous waste	Species extinction
	Radioactive waste	
	Slags/ashes	
	Resources (all)	

Results of the characterization phase for each method are shown in Tables 14 through 18. The impact indicators in each category are approximately the same on average for the wood and

CMU houses. The CMU house performs better than the wood frame house in Tucson and St. Louis. The wood frame house performs better than the CMU house in Lake Charles and Minneapolis.

Table 14. Characterization of Life Cycle Inventory Data Assuming an Egalitarian Perspective Using the Eco-Indicator 99 Method of Characterization

Impact category	Unit*	Wood frame house				
		Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Carcinogens	DALY	2.4E-02	2.5E-02	2.7E-02	2.5E-02	2.7E-02
Respiratory organics	DALY	1.4E-03	1.5E-03	1.7E-03	1.5E-03	1.6E-03
Respiratory inorganics	DALY	1.1E+00	1.2E+00	1.2E+00	1.0E+00	1.0E+00
Climate change	DALY	3.6E-01	3.8E-01	4.4E-01	4.0E-01	4.5E-01
Radiation	DALY	8.1E-04	7.7E-04	1.1E-03	1.1E-03	1.3E-03
Ozone layer	DALY	1.4E-04	1.3E-04	1.9E-04	1.8E-04	2.1E-04
Ecotoxicity	$PAF \cdot m^2 \cdot yr$	5.8E+04	5.9E+04	6.8E+04	6.4E+04	7.1E+04
Acidification/eutrophication	$PDF \cdot m^2 \cdot yr$	3.4E+04	3.7E+04	3.7E+04	3.2E+04	3.2E+04
Land use	$PDF \cdot m^2 \cdot yr$	3.2E+03	3.0E+03	4.3E+03	4.2E+03	5.1E+03
Minerals	MJ surplus	1.0E+04	9.9E+03	1.2E+04	1.2E+04	1.4E+04
Fossil fuels	MJ surplus	2.0E+06	2.0E+06	2.5E+06	2.2E+06	2.6E+06
Impact category	**Unit**	**CMU house**				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Carcinogens	DALY	2.4E-02	2.4E-02	2.7E-02	2.5E-02	2.8E-02
Respiratory organics	DALY	1.4E-03	1.5E-03	1.6E-03	1.5E-03	1.6E-03
Respiratory inorganics	DALY	1.1E+00	1.2E+00	1.2E+00	1.0E+00	1.0E+00
Climate change	DALY	3.7E-01	3.7E-01	4.3E-01	4.0E-01	4.7E-01
Radiation	DALY	8.0E-04	7.1E-04	1.1E-03	1.1E-03	1.4E-03
Ozone layer	DALY	1.4E-04	1.3E-04	1.8E-04	1.8E-04	2.2E-04
Ecotoxicity	$PAF \cdot m^2 \cdot yr$	5.8E+04	5.7E+04	6.6E+04	6.4E+04	7.3E+04
Acidification/eutrophication	$PDF \cdot m^2 \cdot yr$	3.5E+04	3.7E+04	3.6E+04	3.1E+04	3.2E+04
Land use	$PDF \cdot m^2 \cdot yr$	3.2E+03	2.8E+03	4.1E+03	4.3E+03	5.4E+03
Minerals	MJ surplus	1.0E+04	9.5E+03	1.2E+04	1.2E+04	1.4E+04
Fossil fuels	MJ surplus	2.0E+06	1.9E+06	2.4E+06	2.2E+06	2.7E+06
Impact category	**Unit**	**CMU house compared to wood frame house****				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Carcinogens	DALY	-3%	2%	3%	0%	-3%
Respiratory organics	DALY	-2%	2%	3%	2%	-2%
Respiratory inorganics	DALY	-4%	-1%	1%	1%	-2%
Climate change	DALY	-2%	3%	4%	0%	-4%
Radiation	DALY	1%	7%	6%	-2%	-5%
Ozone layer	DALY	0%	6%	5%	-2%	-5%
Ecotoxicity	$PAF \cdot m^2 \cdot yr$	-1%	3%	3%	0%	-2%
Acidification/eutrophication	$PDF \cdot m^2 \cdot yr$	-3%	0%	2%	2%	-1%
Land use	$PDF \cdot m^2 \cdot yr$	0%	6%	5%	-2%	-5%
Minerals	MJ surplus	0%	3%	3%	-2%	-4%
Fossil fuels	MJ surplus	-1%	4%	4%	0%	-4%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. DALY is disability-adjusted life-years; it expresses the number of year-lives lost and the number of year-lives lived with a disability. PAF is potentially affected area. PDF is potentially disappeared fraction. MJ surplus is the additional energy needed for future extractions of scarcer minerals and fossil fuels.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table 15. Characterization of Life Cycle Inventory Data Using a Hierarchic Perspective in the Eco-Indicator 99 Method of Characterization

Impact category	Unit*	Wood frame house				
		Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Carcinogens	DALY	2.4E-02	2.5E-02	2.7E-02	2.5E-02	2.7E-02
Respiratory organics	DALY	1.4E-03	1.5E-03	1.7E-03	1.5E-03	1.6E-03
Respiratory inorganics	DALY	1.1E+00	1.2E+00	1.2E+00	1.0E+00	1.0E+00
Climate change	DALY	3.6E-01	3.8E-01	4.4E-01	4.0E-01	4.5E-01
Radiation	DALY	8.1E-04	7.7E-04	1.1E-03	1.1E-03	1.3E-03
Ozone layer	DALY	1.4E-04	1.3E-04	1.9E-04	1.8E-04	2.1E-04
Ecotoxicity	PAF·m^2·yr	5.8E+04	5.9E+04	6.8E+04	6.4E+04	7.1E+04
Acidification/eutrophication	PDF·m^2·yr	3.4E+04	3.7E+04	3.7E+04	3.2E+04	3.2E+04
Land use	PDF·m^2·yr	3.2E+03	3.0E+03	4.3E+03	4.2E+03	5.1E+03
Minerals	MJ surplus	1.0E+04	9.9E+03	1.2E+04	1.2E+04	1.4E+04
Fossil fuels	MJ surplus	2.2E+06	2.1E+06	3.0E+06	2.8E+06	3.4E+06
Impact category	**Unit**	**CMU house**				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Carcinogens	DALY	2.4E-02	2.4E-02	2.7E-02	2.5E-02	2.8E-02
Respiratory organics	DALY	1.4E-03	1.5E-03	1.6E-03	1.5E-03	1.6E-03
Respiratory inorganics	DALY	1.1E+00	1.2E+00	1.2E+00	1.0E+00	1.0E+00
Climate change	DALY	3.7E-01	3.7E-01	4.3E-01	4.0E-01	4.7E-01
Radiation	DALY	8.0E-04	7.1E-04	1.1E-03	1.1E-03	1.4E-03
Ozone layer	DALY	1.4E-04	1.3E-04	1.8E-04	1.8E-04	2.2E-04
Ecotoxicity	PAF·m^2·yr	5.8E+04	5.7E+04	6.6E+04	6.4E+04	7.3E+04
Acidification/eutrophication	PDF·m^2·yr	3.5E+04	3.7E+04	3.6E+04	3.1E+04	3.2E+04
Land use	PDF·m^2·yr	3.2E+03	2.8E+03	4.1E+03	4.3E+03	5.4E+03
Minerals	MJ surplus	1.0E+04	9.5E+03	1.2E+04	1.2E+04	1.4E+04
Fossil fuels	MJ surplus	2.2E+06	2.0E+06	2.8E+06	2.8E+06	3.5E+06
Impact category	**Unit**	**CMU house compared to wood frame house****				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Carcinogens	DALY	-3%	2%	3%	0%	-3%
Respiratory organics	DALY	-2%	2%	3%	2%	-2%
Respiratory inorganics	DALY	-4%	-1%	1%	1%	-2%
Climate change	DALY	-2%	3%	4%	0%	-4%
Radiation	DALY	1%	7%	6%	-2%	-5%
Ozone layer	DALY	0%	6%	5%	-2%	-5%
Ecotoxicity	PAF·m^2·yr	-1%	3%	3%	0%	-2%
Acidification/eutrophication	PDF·m^2·yr	-3%	0%	2%	2%	-1%
Land use	PDF·m^2·yr	0%	6%	5%	-2%	-5%
Minerals	MJ surplus	0%	3%	3%	-2%	-4%
Fossil fuels	MJ surplus	-1%	6%	5%	-2%	-5%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. DALY is disability-adjusted life-years; it expresses the number of year-lives lost and the number of year-lives lived with a disability. PAF is potentially affected area. PDF is potentially disappeared fraction. MJ surplus is the additional energy needed for future extractions of scarcer minerals and fossil fuels.
**Positive values indicate less impact for CMU house compared to wood frame house.

Table 16. Characterization of Life Cycle Inventory Data Using an Individualist Perspective in the Eco-Indicator 99 Method of Characterization

Impact category	Unit*	Wood frame house				
		Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Carcinogens	DALY	9.1E-03	9.7E-03	1.1E-02	9.5E-03	1.0E-02
Respiratory organics	DALY	1.3E-03	1.4E-03	1.5E-03	1.4E-03	1.5E-03
Respiratory inorganics	DALY	5.2E-01	5.7E-01	5.5E-01	4.8E-01	4.8E-01
Climate change	DALY	3.4E-01	3.6E-01	4.3E-01	3.8E-01	4.3E-01
Radiation	DALY	3.8E-05	3.6E-05	5.0E-05	4.8E-05	5.9E-05
Ozone layer	DALY	1.1E-04	1.1E-04	1.5E-04	1.4E-04	1.7E-04
Ecotoxicity	$PAF \cdot m^2 \cdot yr$	7.3E+03	7.4E+03	8.7E+03	8.1E+03	9.0E+03
Acidification/eutrophication	$PDF \cdot m^2 \cdot yr$	3.4E+04	3.7E+04	3.7E+04	3.2E+04	3.2E+04
Land use	$PDF \cdot m^2 \cdot yr$	3.2E+03	3.0E+03	4.3E+03	4.2E+03	5.1E+03
Minerals	MJ surplus	1.0E+04	9.9E+03	1.2E+04	1.2E+04	1.4E+04
Impact category	**Unit**	**CMU house**				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Carcinogens	DALY	9.3E-03	9.4E-03	1.0E-02	9.4E-03	1.0E-02
Respiratory organics	DALY	1.3E-03	1.4E-03	1.5E-03	1.3E-03	1.5E-03
Respiratory inorganics	DALY	5.4E-01	5.7E-01	5.5E-01	4.8E-01	4.9E-01
Climate change	DALY	3.5E-01	3.5E-01	4.1E-01	3.8E-01	4.4E-01
Radiation	DALY	3.7E-05	3.4E-05	4.7E-05	4.9E-05	6.1E-05
Ozone layer	DALY	1.1E-04	1.0E-04	1.4E-04	1.5E-04	1.8E-04
Ecotoxicity	$PAF \cdot m^2 \cdot yr$	7.3E+03	7.2E+03	8.4E+03	8.1E+03	9.3E+03
Acidification/eutrophication	$PDF \cdot m^2 \cdot yr$	3.5E+04	3.7E+04	3.6E+04	3.1E+04	3.2E+04
Land use	$PDF \cdot m^2 \cdot yr$	3.2E+03	2.8E+03	4.1E+03	4.3E+03	5.4E+03
Minerals	MJ surplus	1.0E+04	9.5E+03	1.2E+04	1.2E+04	1.4E+04
Impact category	**Unit**	**CMU house compared to wood frame house****				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Carcinogens	DALY	-1%	3%	4%	2%	-2%
Respiratory organics	DALY	-2%	2%	3%	2%	-2%
Respiratory inorganics	DALY	-4%	-1%	0%	1%	-2%
Climate change	DALY	-2%	3%	4%	0%	-4%
Radiation	DALY	1%	7%	5%	-2%	-4%
Ozone layer	DALY	0%	6%	5%	-2%	-5%
Ecotoxicity	$PAF \cdot m^2 \cdot yr$	-1%	3%	4%	0%	-3%
Acidification/eutrophication	$PDF \cdot m^2 \cdot yr$	-3%	0%	2%	2%	-1%
Land use	$PDF \cdot m^2 \cdot yr$	0%	6%	5%	-2%	-5%
Minerals	MJ surplus	0%	3%	3%	-2%	-4%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. DALY is disability-adjusted life-years; it expresses the number of year-lives lost and the number of year-lives lived with a disability. PAF is potentially affected area. PDF is potentially disappeared fraction. MJ surplus is the additional energy needed for future extractions of scarcer minerals and fossil fuels.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table 17. Characterization of Life Cycle Inventory Data using the EDIP/UMIP 97 Method of Characterization

Impact category	Unit*	Wood frame house				
		Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Global warming (GWP 100)	g CO_2	1.7E+09	1.8E+09	2.1E+09	1.9E+09	2.2E+09
Ozone depletion	g CFC11	1.3E+02	1.3E+02	1.8E+02	1.7E+02	2.0E+02
Acidification	g SO_2	1.2E+07	1.3E+07	1.3E+07	1.1E+07	1.1E+07
Eutrophication	g NO_3	6.0E+06	6.5E+06	6.6E+06	5.7E+06	5.8E+06
Photochemical smog	g ethene	5.1E+05	5.4E+05	6.1E+05	5.4E+05	6.0E+05
Ecotoxicity water chronic	m^3	9.2E+07	9.5E+07	1.1E+08	1.0E+08	1.1E+08
Ecotoxicity water acute	m^3	9.7E+06	9.9E+06	1.2E+07	1.1E+07	1.2E+07
Ecotoxicity soil chronic	m^3	2.5E+06	2.3E+06	3.7E+06	3.5E+06	4.5E+06
Human toxicity air	m^3	1.7E+11	1.6E+11	2.0E+11	1.9E+11	2.2E+11
Human toxicity water	m^3	4.8E+06	5.1E+06	5.5E+06	5.0E+06	5.4E+06
Human toxicity soil	m^3	7.7E+04	7.4E+04	1.1E+05	1.0E+05	1.3E+05
Bulk waste	kg	1.9E+05	2.1E+05	2.0E+05	1.7E+05	1.7E+05
Hazardous waste	kg	5.7E+01	5.6E+01	6.4E+01	6.4E+01	6.9E+01
Radioactive waste	kg	4.3E+00	4.0E+00	6.5E+00	6.2E+00	8.0E+00
Slags/ashes	kg	3.6E+01	3.5E+01	4.0E+01	4.0E+01	4.4E+01
Resources (all)	kg	5.3E+01	5.2E+01	6.6E+01	6.3E+01	7.4E+01
Impact category	**Unit**	**CMU house**				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Global warming (GWP 100)	g CO_2	1.8E+09	1.8E+09	2.1E+09	1.9E+09	2.2E+09
Ozone depletion	g CFC11	1.3E+02	1.2E+02	1.7E+02	1.7E+02	2.1E+02
Acidification	g SO_2	1.2E+07	1.3E+07	1.2E+07	1.0E+07	1.1E+07
Eutrophication	g NO_3	6.2E+06	6.5E+06	6.5E+06	5.6E+06	5.9E+06
Photochemical smog	g ethene	5.2E+05	5.2E+05	5.8E+05	5.4E+05	6.1E+05
Ecotoxicity water chronic	m^3	9.6E+07	9.4E+07	1.1E+08	1.0E+08	1.2E+08
Ecotoxicity water acute	m^3	9.9E+06	9.7E+06	1.1E+07	1.1E+07	1.3E+07
Ecotoxicity soil chronic	m^3	2.5E+06	2.2E+06	3.4E+06	3.6E+06	4.7E+06
Human toxicity air	m^3	1.7E+11	1.6E+11	2.0E+11	2.0E+11	2.3E+11
Human toxicity water	m^3	5.4E+06	5.6E+06	6.0E+06	5.5E+06	6.0E+06
Human toxicity soil	m^3	7.7E+04	6.8E+04	1.0E+05	1.1E+05	1.4E+05
Bulk waste	kg	2.0E+05	2.1E+05	2.0E+05	1.7E+05	1.7E+05
Hazardous waste	kg	5.7E+01	5.5E+01	6.3E+01	6.4E+01	7.1E+01
Radioactive waste	kg	4.3E+00	3.6E+00	6.1E+00	6.4E+00	8.5E+00
Slags/ashes	kg	3.4E+01	3.3E+01	3.8E+01	3.9E+01	4.3E+01
Resources (all)	kg	5.3E+01	5.0E+01	6.4E+01	6.4E+01	7.7E+01

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table 17. Characterization of Life Cycle Inventory Data using the EDIP/UMIP 97 Method of Characterization (Continued)

Impact category	Unit	CMU house compared to wood frame house**				
		Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Global warming (GWP 100)	g CO_2	-2%	3%	4%	0%	-4%
Ozone depletion	g CFC11	0%	6%	5%	-2%	-5%
Acidification	g SO_2	-2%	0%	2%	3%	0%
Eutrophication	g NO_3	-3%	0%	2%	2%	-2%
Photochemical smog	g ethene	-1%	3%	4%	1%	-2%
Ecotoxicity water chronic	m^3	-3%	0%	1%	-2%	-5%
Ecotoxicity water acute	m^3	-2%	2%	3%	-1%	-4%
Ecotoxicity soil chronic	m^3	-1%	7%	6%	-3%	-6%
Human toxicity air	m^3	-1%	4%	4%	-1%	-4%
Human toxicity water	m^3	-14%	-10%	-8%	-10%	-13%
Human toxicity soil	m^3	0%	7%	6%	-3%	-5%
Bulk waste	kg	-3%	0%	1%	3%	0%
Hazardous waste	kg	0%	2%	2%	-1%	-2%
Radioactive waste	kg	0%	9%	7%	-3%	-6%
Slags/ashes	kg	4%	6%	6%	3%	1%
Resources (all)	kg	-1%	4%	4%	-2%	-4%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000.
**Positive values indicate less impact for CMU house compared to wood frame house.

Table 18. Characterization of Life Cycle Inventory Data using the EPS 2000 Method of Characterization

Impact category	Unit*	Wood frame house				
		Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Life expectancy	PersonYr	2.1E+00	2.3E+00	2.6E+00	2.3E+00	2.5E+00
Severe morbidity	PersonYr	5.6E-01	5.8E-01	7.1E-01	6.4E-01	7.3E-01
Morbidity	PersonYr	1.2E+00	1.3E+00	1.5E+00	1.4E+00	1.5E+00
Severe nuisance	PersonYr	1.7E-01	1.7E-01	1.8E-01	1.8E-01	1.8E-01
Nuisance	PersonYr	6.8E+01	7.4E+01	7.3E+01	6.2E+01	6.1E+01
Crop growth capacity	kg	4.7E+03	4.9E+03	5.5E+03	4.8E+03	5.2E+03
Wood growth capacity	kg	-7.8E+04	-8.2E+04	-9.4E+04	-8.3E+04	-9.3E+04
Fish and meat production	kg	-1.4E+02	-1.5E+02	-1.5E+02	-1.3E+02	-1.3E+02
Soil acidification	H+ eq.	1.8E+04	2.0E+04	2.0E+04	1.7E+04	1.7E+04
Prod. cap. irrigation water	kg	8.1E+01	8.1E+01	8.1E+01	8.1E+01	8.1E+01
Prod. cap. drinking water	kg	8.1E+01	8.1E+01	8.1E+01	8.1E+01	8.1E+01
Depletion of reserves	ELU	4.5E+05	4.4E+05	6.0E+05	5.6E+05	6.8E+05
Species extinction	NEX	2.0E-08	2.1E-08	2.5E-08	2.2E-08	2.6E-08
Impact category	**Unit**	**CMU house**				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Life expectancy	PersonYr	2.2E+00	2.2E+00	2.5E+00	2.3E+00	2.6E+00
Severe morbidity	PersonYr	5.7E-01	5.6E-01	6.8E-01	6.4E-01	7.6E-01
Morbidity	PersonYr	1.3E+00	1.3E+00	1.5E+00	1.4E+00	1.6E+00
Severe nuisance	PersonYr	1.7E-01	1.7E-01	1.8E-01	1.8E-01	1.9E-01
Nuisance	PersonYr	6.9E+01	7.4E+01	7.1E+01	6.0E+01	6.1E+01
Crop growth capacity	kg	4.8E+03	4.9E+03	5.3E+03	4.8E+03	5.4E+03
Wood growth capacity	kg	-7.9E+04	-8.0E+04	-9.1E+04	-8.3E+04	-9.6E+04
Fish and meat production	kg	-1.4E+02	-1.5E+02	-1.5E+02	-1.3E+02	-1.4E+02
Soil acidification	H+ eq.	1.9E+04	2.0E+04	1.9E+04	1.6E+04	1.7E+04
Prod. cap. irrigation water	kg	8.1E+01	8.1E+01	8.1E+01	8.1E+01	8.1E+01
Prod. cap. drinking water	kg	8.1E+01	8.1E+01	8.1E+01	8.1E+01	8.1E+01
Depletion of reserves	ELU	4.5E+05	4.2E+05	5.7E+05	5.7E+05	7.1E+05
Species extinction	NEX	2.0E-08	2.0E-08	2.4E-08	2.3E-08	2.7E-08
Impact category	**Unit**	**CMU house compared to wood frame house****				
		Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Life expectancy	PersonYr	-3%	1%	3%	0%	-3%
Severe morbidity	PersonYr	-2%	3%	4%	-1%	-4%
Morbidity	PersonYr	-2%	2%	3%	0%	-3%
Severe nuisance	PersonYr	0%	1%	1%	0%	-1%
Nuisance	PersonYr	-2%	0%	2%	3%	0%
Crop growth capacity	kg	-2%	1%	3%	1%	-3%
Wood growth capacity	kg	-2%	2%	3%	0%	-3%
Fish and meat production	kg	-3%	0%	1%	1%	-2%
Soil acidification	H+ eq.	-2%	0%	2%	3%	0%
Prod. cap. irrigation water	kg	0%	0%	0%	0%	0%
Prod. cap. drinking water	kg	0%	0%	0%	0%	0%
Depletion of reserves	ELU	-1%	5%	5%	-2%	-4%
Species extinction	NEX	-2%	3%	4%	-1%	-4%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. ELU is environmental load unit. NEX is no extinction.

**Positive values indicate less impact for CMU house compared to wood frame house.

Other methods of impact assessment, such as damage assessment, normalization, and weighting, are optional. In damage assessment, impact categories that have equivalent units are added. In normalization, the impact assessment values are compared to some reference, such as the average yearly environmental load in a country divided by the number of people in the country. In weighting, the impact assessment values in several or all categories are multiplied by weighting factors and added together to get a single score. However, the weighting factors used are always subjective and reflect societal or personal values. Furthermore, according to *ISO 14042*, weighting cannot be used to make comparative assertions disclosed to the public. The tables in Appendix C show the normalized and weighted results for each category of each method. In each of the five methods, the CMU house has a lower score than the wood frame house in almost all impact categories in Tucson and St. Louis. The CMU house has a higher score than the wood frame house in almost all impact categories in Lake Charles and Minneapolis. In Denver the scores are approximately equal. A summary of the normalized and weighted single-score results is shown in Table 19.

Table 19. Normalized and Weighted Single Score Summary

House style	Location	Method				
		Eco-Indicator 99			EDIP/ UMIP 97	EPS 2000
		Egalitarian	Hierarchic	Individualist		
Wood frame house	Lake Charles	99,000	110,000	74,000	2,730	707,000
	Tucson	103,000	111,000	78,000	2,760	712,000
	St. Louis	121,000	142,000	85,000	3,480	910,000
	Denver	108,000	130,000	76,000	3,220	840,000
	Minneapolis	121,000	154,000	82,000	3,760	986,000
CMU house	Lake Charles	101,000	111,000	76,000	2,800	716,000
	Tucson	101,000	107,000	77,000	2,690	685,000
	St. Louis	116,000	136,000	83,000	3,370	872,000
	Denver	108,000	132,000	76,000	3,290	850,000
	Minneapolis	125,000	160,000	84,000	3,940	1,027,000

LIFE CYCLE INTERPRETATION

Life cycle interpretation is the "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 2006b).

A breakdown of the LCA by major process and product stage shows that most of the environmental load is from the household use of natural gas and electricity during the life of the houses. Figure 2 shows the breakdown for each house using the hierarchic perspective of Eco-Indicator 99. The household-use of electricity and natural gas represents 97% of the environmental impacts of the CMU houses and 97% of the environmental impacts of the wood frame houses. Because energy use is the dominant factor in LCA results, the results comparing energy use of CMU to wood frame in Table 7 are similar to the resulting comparisons in Tables 14 to 18.

The household use of electricity (mostly for cooling) contributes the most to the total environmental impacts in cooling-dominant climates like Tucson. The household use of natural gas (mostly for heating) contributes the most to the total environmental impacts in heating-dominant climates like Minneapolis. In all locations, cement-based materials represent a small fraction of the total environmental impacts. Furthermore, the data in Figure 2 show that the most significant impact categories are fossil fuel depletion and respiratory inorganics. The other methods of life cycle impact assessment produce similar results.

Figure 3 shows a breakdown of the environmental impacts of buildings materials for each of the houses using the hierarchic perspective of the Eco-Indicator 99 Method. Most of the environmental impacts from construction materials are due to aluminum siding, ceramic tiles, paint, roof shingles, cement-based materials, steel, and cast iron. Furthermore, the impact categories that contribute the most to the total environmental impacts are fossil fuel depletion and respiratory inorganics.

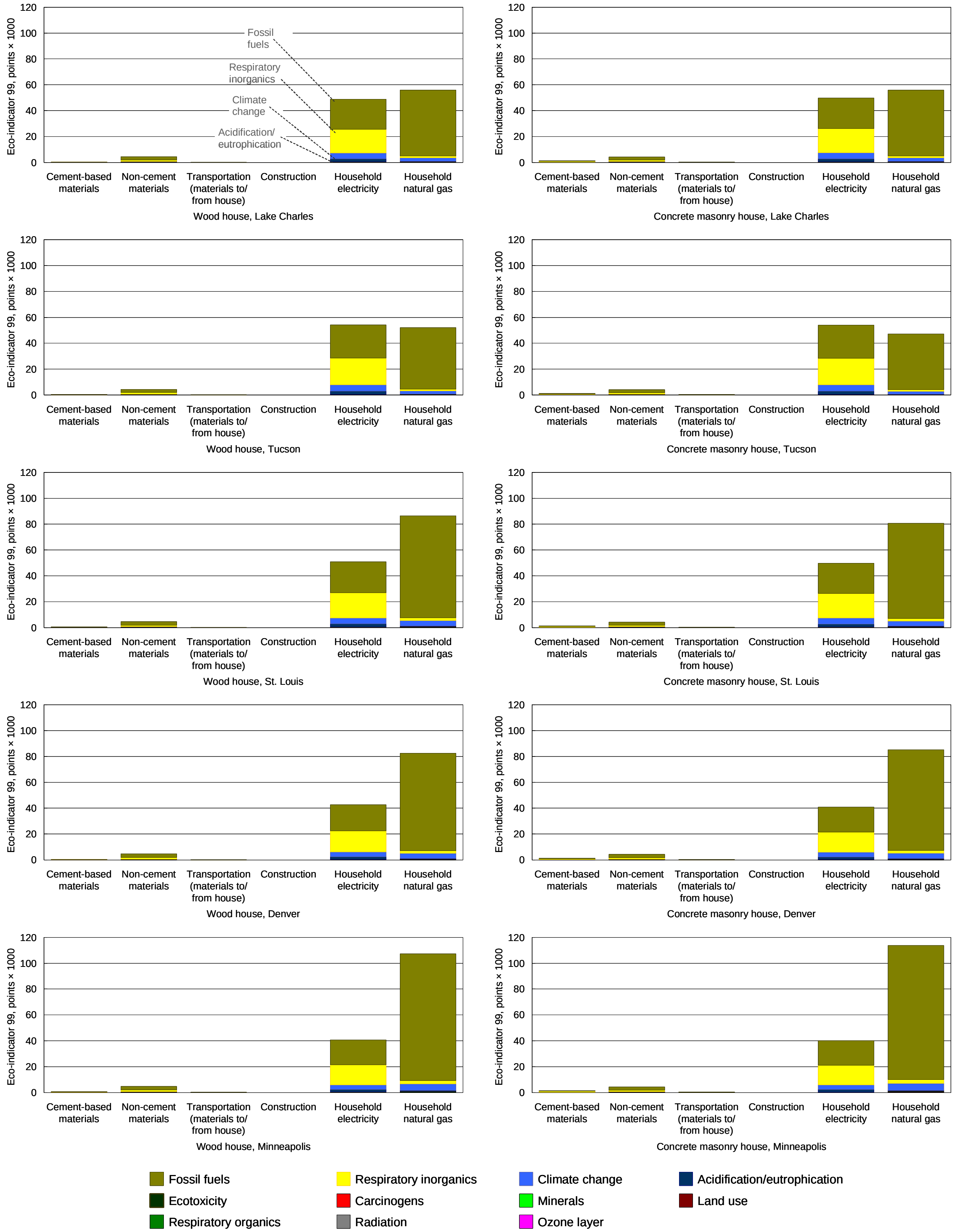

Figure 2. Single-score life cycle inventory assessment of houses showing contribution of each major product and process stage. The data have been normalized and weighted according to the Eco-Indicator 99 method using the Hierarchic perspective.

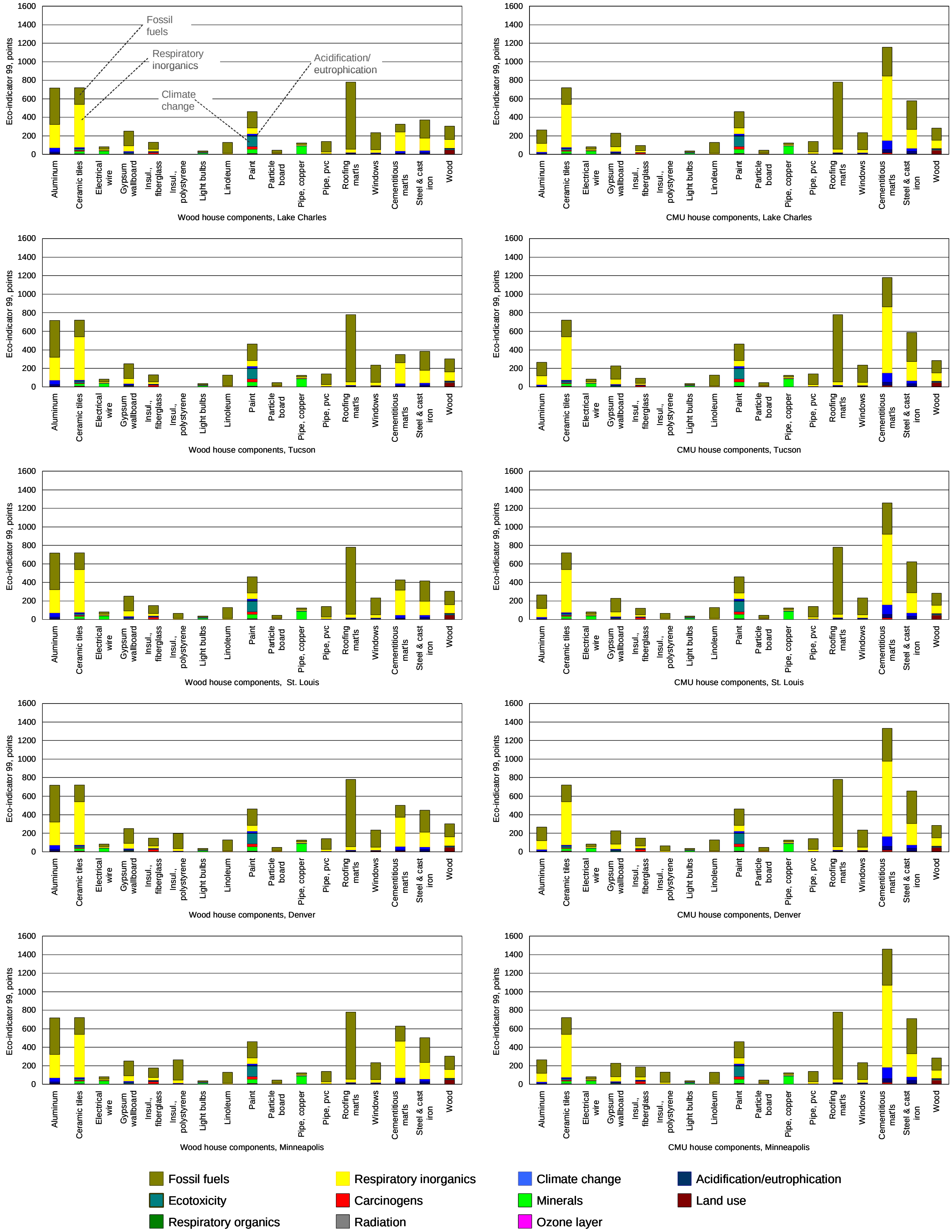

Figure 3. Single-score life cycle inventory assessment of construction materials in the houses showing contribution of each major product and process stage. The data have been normalized and weighted according to the Eco-Indicator 99 method using the Hierarchic perspective.

Sensitivity

Approximately 95% of the negative environmental impacts are associated with household use of electricity and natural gas (including the environmental impacts embodied in the electricity and natural gas). Similarly, approximately 95% of the life cycle energy use is from household use of electricity and natural gas. Less than 0.5% of the life cycle energy use is embodied in the concrete portion of the house. Therefore, the house life cycle energy use is not sensitive to variations in cement manufacturing or concrete production. Furthermore, after climate, occupant behavior is the single most important factor contributing to energy consumption in houses. As a result, the house life cycle energy use is a function of climate and occupant behavior, not concrete content.

CONCLUSIONS

This report presents the results of an assessment of the environmental attributes of concrete construction compared to wood-framed construction. A life cycle assessment (LCA) was conducted on a house modeled with two types of exterior walls: a wood-framed wall and a CMU wall. The LCA was carried out according to the guidelines in *International Standard ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. The house was modeled in five cities, representing a range of U.S. climates: Lake Charles, Tucson, St. Louis, Denver, and Minneapolis. Each house is a two-story single-family building with a contemporary design. The house system boundary includes the inputs and outputs of energy and material from construction, occupancy, maintenance, demolition, and disposal. The system boundary excludes capital goods, human labor, impacts caused by people, and waste treatment after disposal. An LCA of buildings typically does not include measures of disaster resistance, occupant comfort, or occupant productivity. The life of the houses is 100 years.

The LCA was conducted by first assembling the relevant LCI data from published reports and commercially available databases. The LCA software tool, SimaPro, was used to perform a life cycle impact assessment. Impact assessment is not completely scientific, so three different models were used. The methods chosen are Eco-Indicator 99 (Dutch/Swiss), EDIP/UMIP 97 (Danish), and EPS 2000 (Swedish). Furthermore, three different weighting sets in Eco-Indicator 99 were used.

The data show that in all cases for all five methods, on average, the impact indicators in each category are similar for the wood and CMU houses. The most significant environmental impacts are not from construction materials but from the production of electricity and natural gas and the use of electricity and natural gas in the houses by the occupants. Furthermore, the largest impacts from these uses are in the form of depletion of fossil fuel reserves (categorized as damage to natural resources) and release to the air of respiratory inorganics (categorized as damage to human health).

The household use of electricity and natural gas represents 97% of the negative impacts in the CMU house, and 97% of the negative impacts in the wood frame house. For this reason, energy use is a predictor of LCA results. The CMU house has similar energy performance as the wood frame house even though the CMU house has significantly less added insulation. This is due to the thermal mass of the concrete.

When considering only the construction materials, most of the environmental impacts are from aluminum siding, ceramic tiles, paint, roof shingles, cement-based materials, steel, and cast iron.

ACKNOWLEDGEMENTS

The research reported in this paper (PCA R&D Serial No. 3042) was conducted by CTLGroup with the sponsorship of the Portland Cement Association (PCA Project Index No. 06-01). The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association.

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APPENDIX A – HOUSE PLANS AND WALL CROSS-SECTIONS

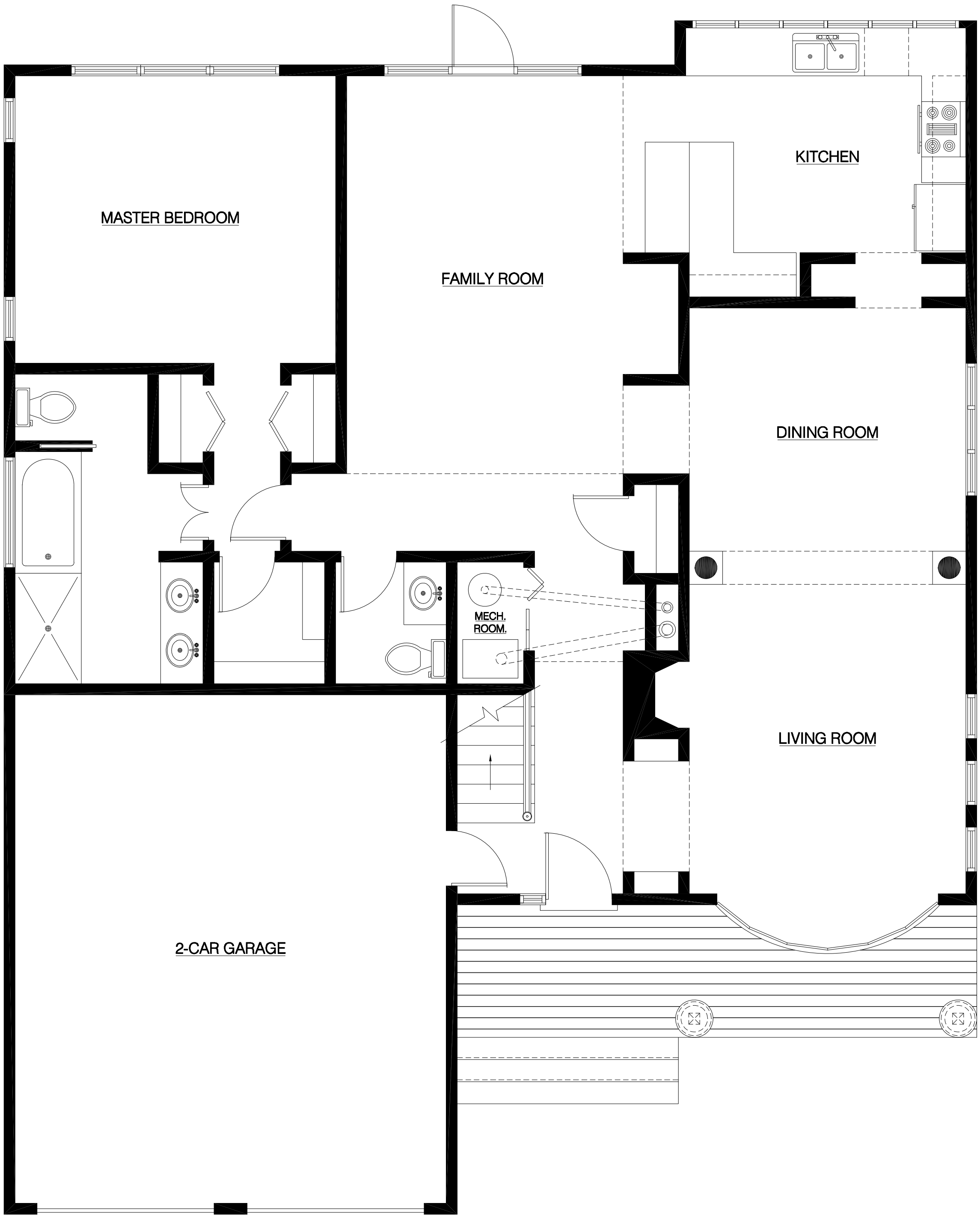

Figure A-1. Floor plan of the lower level (ground floor).

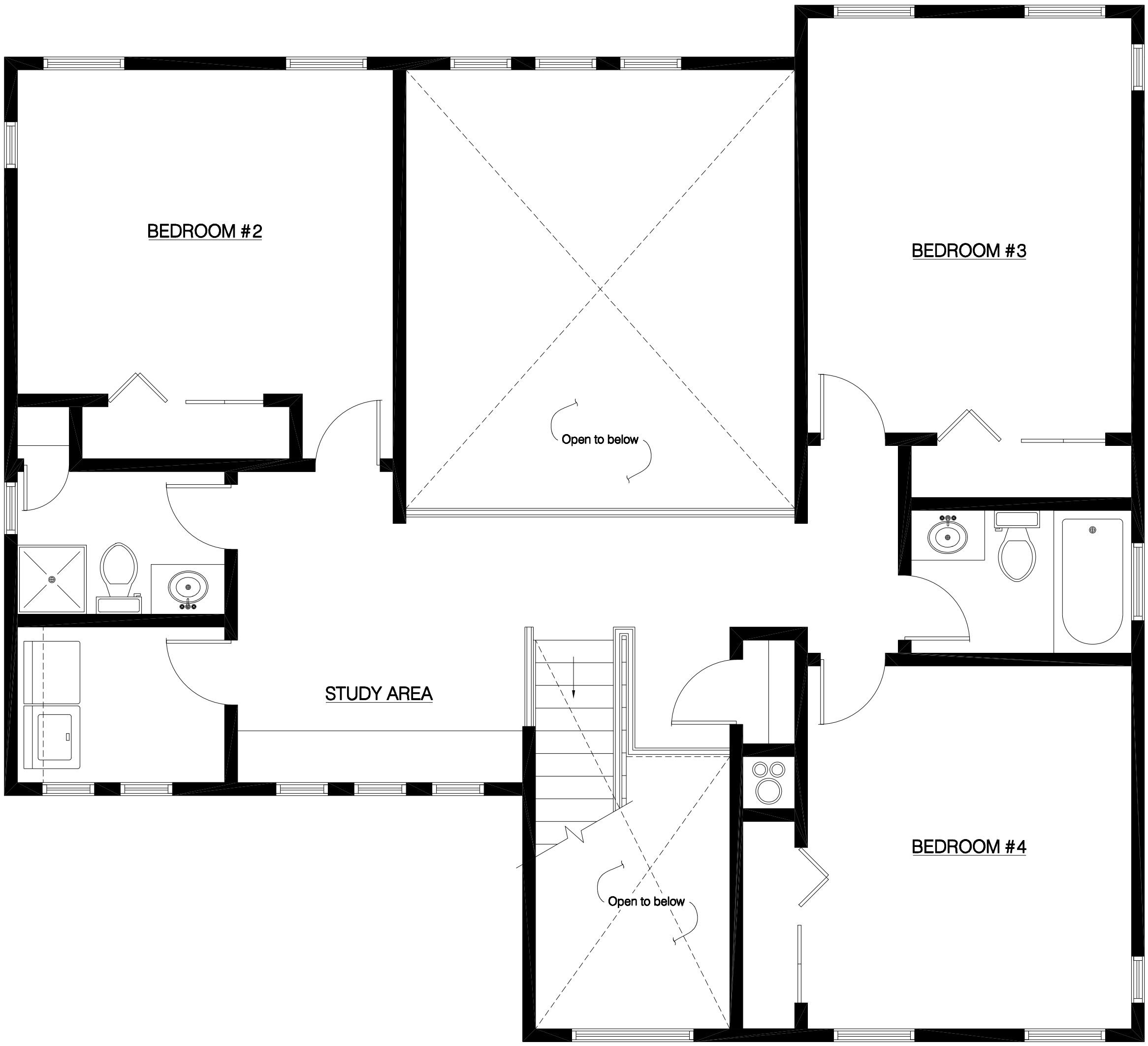

Figure A-2. Floor plan of the upper level (second floor).

Figure A-3. Front elevation.

Figure A-4. Rear elevation.

Figure A-5. Right elevation.

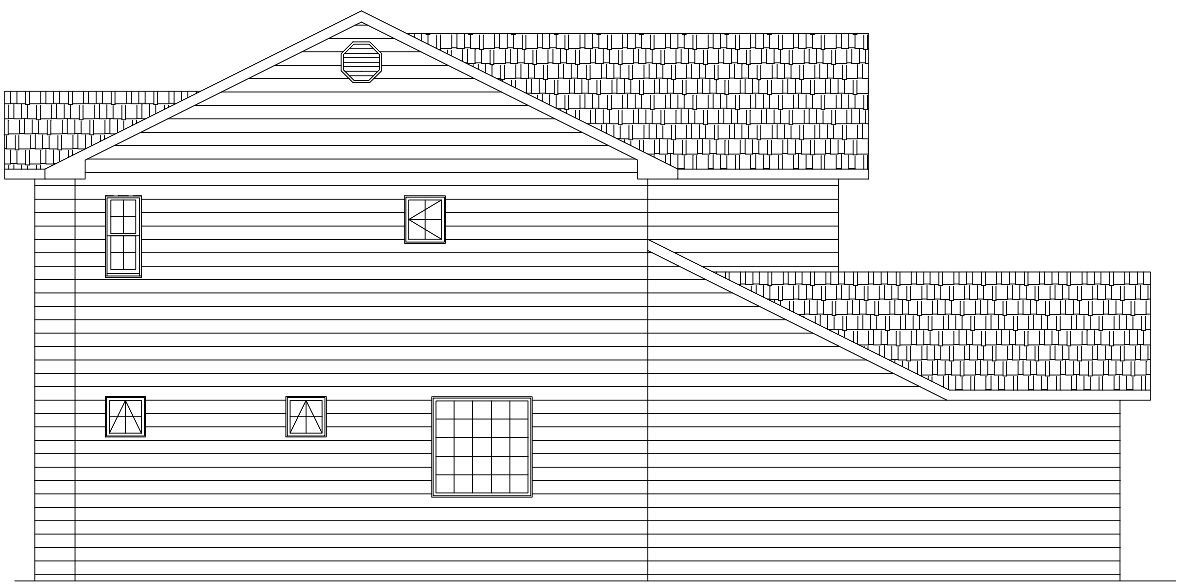

Figure A-6. Left elevation.

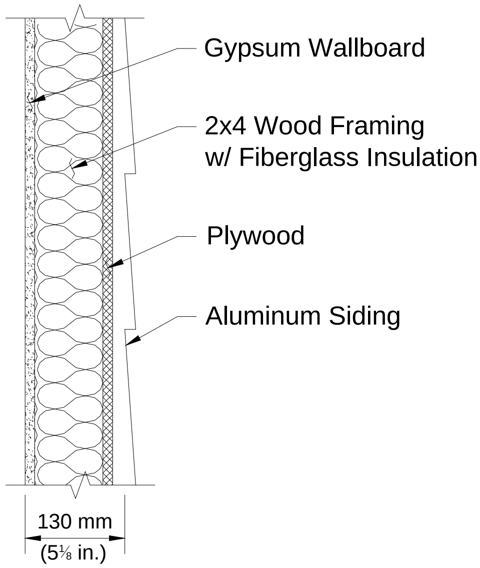

Figure A-7. Wood frame wall cross-section.

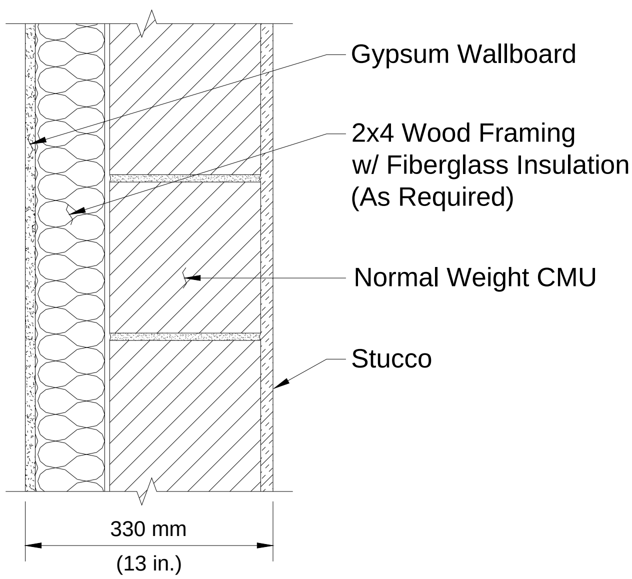

Figure A-8. CMU wall cross-section.

APPENDIX B – IMPACT ASSESSMENT METHODS

This appendix contains a description of the impact assessment methods, copied with permission, from Goedkoop, Mark, Oele, Michiel, and Effting, Suzanne, *SimaPro Database Manual: Methods library*, PRé Consultants, Amersfoort, The Netherlands, 2004, 34 pages.

2.4 Eco-indicator 99 v2.1

2.4.1 Introduction

Eco-indicator 99 is the successor of Eco-indicator 95. Both methods use the damage-oriented approach. The development of the Eco-indicator 99 methodology started with the design of the weighting procedure. Traditionally in LCA the emissions and resource extractions are expressed as 10 or more different impact categories, like acidification, ozone layer depletion, ecotoxicity and resource extraction. For a panel of experts or non-experts it is very difficult to give meaningful weighting factors for such a large number and rather abstract impact categories. It was concluded that the panel should not be asked to weight the impact categories but the different types of damage that are caused by these impact categories. The other improvement was to limit the number of items that are to be assessed. As a result the panel, consisting of 365 persons from a Swiss LCA interest group, was asked to assess the seriousness of three damage categories:

1. Damage to Human Health, expressed as the number of year life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs), an index that is also used by the Worldbank and WHO.
2. Damage to Ecosystem Quality, express as the loss of species over an certain area, during a certain time
3. Damage to Resources, expressed as the surplus energy needed for future extractions of minerals and fossil fuels.

In order to be able to use the weights for the three damage categories a series of complex damage models had to be developed. In figure 2 these models are represented in a schematic way.

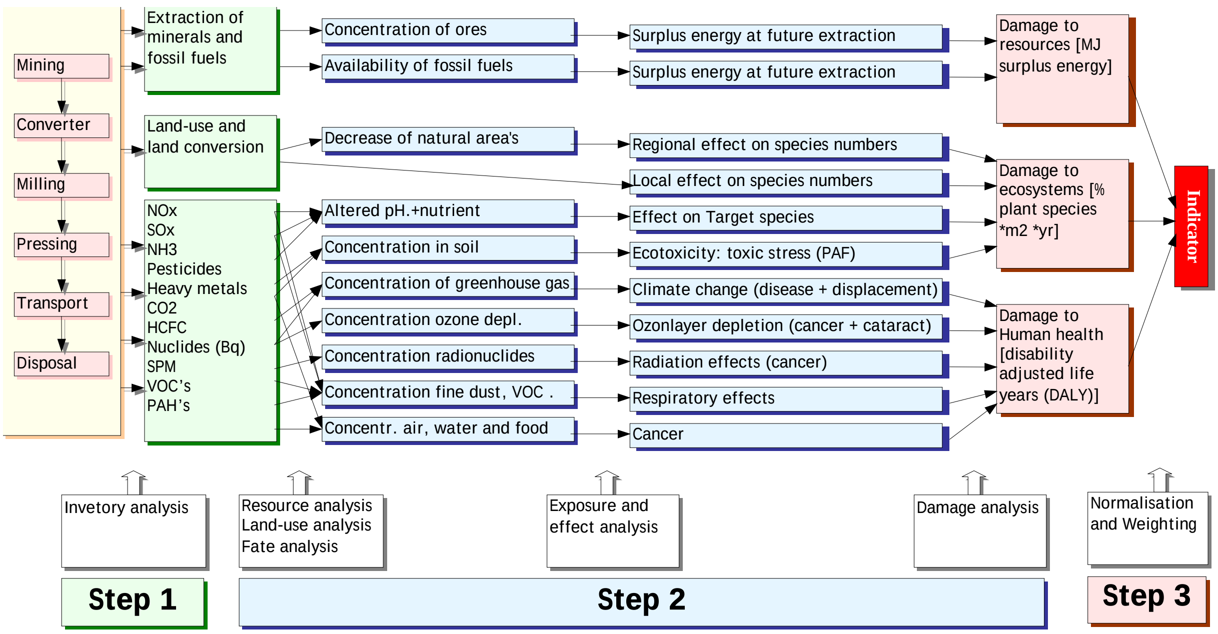

Figure 1: Detailed representation of the damage model

In general, the factors used in SimaPro do not deviate from the ones in the (updated) report. In case the report contained synonyms of substance names already available in the substance list of the SimaPro database, the existing names in the database are used. A distinction is made for emissions to agricultural soil and industrial soil, indicated with respectively (agr.) or (ind.) behind substance names emitted to soil.

2.4.2 Characterisation

Emissions

Characterisation is factors are calculated at end-point level (damage). The damage model for emissions includes fate analysis, exposure, effects analysis and damage analysis.
This model is applied for the following impact categories:

- **Carcinogens**
  Carcinogenic affects due to emissions of carcinogenic substances to air, water and soil. Damage is expressed in Disability adjusted Life Years (DALY) / kg emission.

- **Respiratory organics**
  Respiratory effects resulting from summer smog, due to emissions of organic substances to air, causing respiratory effects. Damage is expressed in Disability adjusted Life Years (DALY) / kg emission.

- **Respiratory inorganics**
  Respiratory effects resulting from winter smog caused by emissions of dust, sulphur and nitrogen oxides to air. Damage is expressed in Disability adjusted Life Years (DALY) / kg emission.

- **Climate change**
  Damage, expressed in DALY/kg emission, resulting from an increase of diseases and death caused by climate change.

- **Radiation**
  Damage, expressed in DALY/kg emission, resulting from radioactive radiation

- **Ozone layer**
  Damage, expressed in DALY/kg emission, due to increased UV radiation as a result of emission of ozone depleting substances to air.

- **Ecotoxicity**
  Damage to ecosystem quality, as a result of emission of ecotoxic substances to air, water and soil. Damage is expressed in Potentially Affected Fraction (PAF)*m2*year/kg emission.

- **Acidification/ Eutrophication**
  Damage to ecosystem quality, as a result of emission of acidifying substances to air. Damage is expressed in Potentially Disappeared Fraction (PDF)*m2*year/kg emission.

Land use

Land use (in man made systems) has impact on species diversity. Based on field observations, a scale is developed expressing species diversity per type of land use. Species diversity depends on the type of land use and the size of the area. Both regional effects and local effects are taken into account in the impact category:

- **Land use**
  Damage as a result of either conversion of land or occupation of land. Damage is expressed in Potentially Disappeared Fraction (PDF)*m2*year/m2 or m2a.

Resource depletion

Mankind will always extracts the best resources first, leaving the lower quality resources for future extraction. The damage of resources will be experienced by future generations, as they will have to use more effort to extract remaining resources. This extra effort is expressed as “surplus energy”.

- **Minerals**
  Surplus energy per kg mineral or ore, as a result of decreasing ore grades.

- **Fossil fuels**
  Surplus energy per extracted MJ, kg or m3 fossil fuel, as a result of lower quality resources.

2.4.3 Uncertainties

Of course it is very important to pay attention to the uncertainties in the methodology that is used to calculate the indicators. Two types are distinguished:

1. Uncertainties about the correctness of the models used
2. Data uncertainties

Data uncertainties are specified for most damage factors as squared geometric standard deviation in the original reports, but not in the method in SimaPro. It is not useful to express the uncertainties of the model as a distribution. Uncertainties about the model are related to subjective choices in the model. In order to deal with them we developed three different versions of the methodology, using the archetypes specified in Cultural Theory. The three versions of Eco-indicator 99 are:

1. the egalitarian perspective
2. the hierarchist perspective
3. the individualist perspective

Hierchist perspective

In the hierarchist perspective the chosen time perspective is long-term, substances are included if there is consensus regarding their effect. For instance all carcinogenic substances in IARC class 1, 2a and 2b are included, while class 3 has deliberately been excluded. In the hierarchist perspective damages are assumed to be avoidable by good management. For instance the danger people have to flee from rising water levels is not included. In the case of fossil fuels the assumption is made that fossil fuels cannot easily be substituted. Oil and gas are to be replaced by shale, while coal is replaced by brown coal. In the DALY calculations age weighting is not included.

Egalitarian perspective

In the egalitarian perspective the chosen time perspective is extremely long-term, Substances are included if there is just an indication regarding their effect. For instance all carcinogenic substances in IARC class 1, 2a, 2b and 3 are included, as far as information was available. In the egalitarian perspective, damages cannot be avoided and may lead to catastrophic events. In the case of fossil fuels the assumption is made that fossil fuels cannot be substituted. Oil, coal and gas are to be replaced by a future mix of brown coal and shale. In the DALY calculations age weighting is not included.

Individualist perspective

In the individualist perspective the chosen time perspective is short-term (100 years or less). Substances are included if there is complete proof regarding their effect. For instance only carcinogenic substances in IARC class 1 included, while class 2a, 2b and 3 have deliberately been excluded. In the individualist perspective damages are assumed to be recoverable by technological and economic development. In the case of fossil fuels the assumption is made that fossil fuels cannot really be depleted. Therefore they are left out. In the DALY calculations age weighting is included.

Damage assessment

Damages of the impact categories result in three types of damages:

1. Damage to **Human Health**, expressed as the number of year life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs), an index that is also used by the World bank and the WHO.
2. Damage to **Ecosystem Quality**, express as the loss of species over an certain area, during a certain time
3. Damage to **Resources**, expressed as the surplus energy needed for future extractions of minerals and fossil fuels.

2.4.4 Normalisation

Normalisation is performed on damage category level. Normalisation data is calculated on European level, mostly based on 1993 as base years, with some updates for the most important emissions.

2.4.5 Weighting

In this method weighting is performed at damage category level (endpoint level in ISO). A panel performed weighting of the three damage categories. For each perspective, a specific weighting set is available. The average result of the panel assessment is available as weighting set.

2.4.6 Default

The hierchist version of Eco-indicator 99 with average weighting is chosen default. In general value choices made in the hierachist version are scientifically and politically accepted.

2.6 EPS 2000 v2.1

2.6.1 Introduction

The EPS 2000 default methodology (Environmental Priority Strategies in product design) is a damage oriented method. In the EPS system willingness to pay to restore changes in the safe guard subjects is chosen as the monetary measure. The indicator unit is ELU (Environmental Load Unit). This method includes characterisation and weighting. Normalisation is not applied.

The top-down development of the EPS system has led to an outspoken hierarchy among its principles and rules. The general principles of its development are:

- The top-down principle (highest priority is given to the usefulness of the system);
- The index principle (ready made indices represent weighted and aggregated impacts)
- The default principle (an operative method as default is required)
- The uncertainty principle (uncertainty of input data has to be estimated)
- Choice of default data and models to determine them

The EPS system is mainly aimed to be a tool for a company's internal product development process. The system is developed to assist designers and product developers in finding which one of two product concepts has the least impact on the environment. The models and data in EPS are intended to improve environmental performance of products. The choice and design of the models and data are made from an anticipated utility perspective of a product developer. They are, for instance not intended to be used as a basis for environmental protection strategies for single substances, or as a sole basis for environmental product declarations. In most of those cases additional site-specific information and modelling is necessary.

The EPS 2000 default method is an update of the 1996 version. The impact categories are identified from five safe guard subjects: human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values.

2.6.2 Classification

Emissions and resources are assigned to impact categories when actual effects are likely to occur in the environment, based on likely exposure.

2.6.3 Characterisation

Empirical, equivalency and mechanistic models are used to calculate default characterisation values.

Human Health

In EPS weighting factors for damage to human health are included for the following indictors:
- Life expectancy, expressed in Years of life lost (person year)
- Severe morbidity and suffering, in person year, including starvation
- Morbidity, in person year, like cold or flu
- Severe nuisance, in person year, which would normally cause a reaction to avoid the nuisance
- Nuisance, in person year, irritating, but not causing any direct action

Ecosystem production capacity

The default impact categories of production capacity of ecosystems are:
- Crop production capacity, in kg weight at harvest
- Wood production capacity, in kg dry weight
- Fish and meat production capacity, in kg full weight of animals
- Base cat-ion capacity, in H+ mole equivalents (used only when models including the other indicators are not available)
- Production capacity of (irrigation) water, in kg which is acceptable for irrigation, with respect to persistant toxic substances
- Production capacity of (drinking) water, in kg of water fulfilling WHO criteria on drinking water.

Abiotic stock resources

Abiotic stock resource indicators are depletion of elemental or mineral reserves and depletion of fossil reserves. Some classification factors are defined 0 (zero).
In SimaPro characterisation values for abiotic depletion result from both the impact of depletion and impacts due to extraction of the element/mineral or resource.

Biodiversity

Default impact category for biodiversity is extinction of species, expressed in Normalised Extinction of species (NEX).

Cultural and recreational values

Changes in cultural and recreational values are difficult to describe by general indicators as they are highly specific and qualitative in nature. Indicators should be defined when needed, and thus are not included in the default methodology in SimaPro.

2.6.4 Weighting

In the EPS default method, weighting is made through valuation. Weighting factors represent the willingness to pay to avoid changes. The environmental reference is the present state of the environment. The indicator unit is ELU (Environmental Load Unit).

2.6.5 References:

Bengt Steen (1999) A systematic approach to environmental strategies in product development (EPS). Version 2000 - General system characteristics. Centre for Environmental Assessment of Products and Material Systems. Chalmers University of Technology, Technical Environmental Planning. CPM report 1999:4.
Download as PDF file (246 kb) from http://www.cpm.chalmers.se/cpm/publications/EPS2000.PDF

Bengt Steen (1999) A systematic approach to environmental strategies in product development (EPS). Version 2000 - Models and data of the default methods. Centre for Environmental Assessment of Products and Material Systems. Chalmers University of Technology, Technical Environmental Planning. CPM report 1999:5.
Download as zipped PDF file (1140 kb) from
http://www.cpm.chalmers.se/cpm/publications/EPS1999_5.zip

2.7 EDIP v2.1

2.7.1 Introduction

The EDIP method (Environmental Design of Industrial Products, in Danish UMIP) was developed in 1996. Excluded in this version of the method in SimaPro are working environment and emissions to waste water treatment plants (WWTP). An update of the method is expected by the beginning of 2002.

2.7.2 Characterisation

Global warming is based on the IPCC 1994 Status report. Is SimaPro GWP 100 is used. Stratospheric ozone depletion potentials are based on the status reports (1992/1995) of the Global Ozone Research Project (infinite time period used in SimaPro). Photochemical ozone creation potentials (POCP) were taken from UNECE reports (1990/1992). POCP values depend on the background concentration of NOx, in SimaPro we have chosen to use the POCPs for high background concentrations. Acidification is based on the number of hydrogen ions (H+) that can be released. Eutrophication potential is based on N and P content in organisms. Waste streams are divided in 4 categories, bulk waste (not hazardous), hazardous waste, radioactive waste and slags and ashes. All wastes are reported on a mass basis.

Ecotoxicity is based on a chemical hazard screening method, which looks at toxicity, persistency and bioconcentration. Fate or the distribution of substances into various environmental compartments is also taken account. Ecotoxicity potentials are calculated for acute and chronic ecotoxicity to water and chronic ecotoxicity for soil. As fate is included, an emission to water may lead not only to chronic and acute ecotoxicity for water, but also to soil. Similarly an emission to air gives ecotoxicity for water and soil. This is the reason you will find emissions to various compartments in each ecotoxicity category.

Human toxicity is based on a chemical hazard screening method, which looks at toxicity, persistency and bioconcentration. Fate or the distribution of substances into various environmental compartments is also taken account. Human toxicity potentials are calculated for exposure via air, soil, and surface water. As fate is included, an emission to water may lead not only to toxicity via water, but also via soil. Similarly an emission to air gives human toxicity via water and soil. This is the reason you will find emissions to various compartments in each human toxicity category.

Resources

As resources use a different method of weighting, it cannot be compared with the other impact categories, for which reason the weighting factor is set at zero. Resources should be handled with great care when analysing results, the characterisation and normalisation results cannot be compared with the other impact categories.
To give the user some information in a useful way all resources have been added into one impact category. As equivalency factor the result of the individual normalisation and weighting scores have been used, i.e. the resulting score per kg if they would have been calculated individually.
For detailed information on resources, including normalisation and weighting, choose the "EDIP/UMIP resources only" method.

EDIP v2.0 resources only
In the "EDIP/UMIP resources only" method only resources are reported. Opposite to the default EDIP/UMIP method, resources are given in individual impact categories, on a mass basis of the pure resource (i.e. 100% metal in ore, rather than ore). Normalisation is based on global production per world citizen, derived from World Resources 1992. Weighting of non-renewables is based on the supply-horizon (World Reserves Life Index), which specifies the period for which known reserves will last at current rates of consumption. If no normalisation data are known for an individual impact category, the normalisation value is set at one and the calculation of the weighting factor is adjusted so that the final result is still consistent. However this may give strange looking graphs in the normalisation step.

2.7.3 Normalisation

The normalisation value is based on person equivalents for 1990. For resources, normalisation and weighing are already included in the characterisation factor and therefore set at zero.

2.7.4 Weighting

The weighting factors are set to the politically set target emissions per person in the year 2000, the weighted result are expressed except for resources which is based on the proven reserves per person in 1990. For resources, normalisation and weighing are already included in the characterisation factor and therefore set at zero.

A note on weighting:
Presenting the EDIP method as a single score (addition) is allowed, however it is not recommended by the authors. Note that due to a different weighting method for resources (based on reserves rather than political targets), resources may never be included in a single score. This is the reason that the weighting factor for resources is set at zero.

2.7.5 References:

For background information, and information on how to calculate additional factors, please read:

Environmental Assessment of Products.
Volume 1 (methodology, tools and case studies in product development)
Henrik Wenzel, Michael Hauschild and Leo Alting
Chapman and Hall, 1997, ISBN 0 412 80800 5
See http://www.wkap.nl/book.htm/0-7923-7859-8

Environmental Assessment of Products.
Volume 2 (scientific background)
Michael Hauschild and Henrik Wenzel
Chapman and Hall, 1998, ISBN 0 412 80810 2
See http://www.wkap.nl/book.htm/0-412-80810-2

APPENDIX C – NORMALIZED AND WEIGHTED LCA RESULTS

Table C-1. Normalized and Weighted LCA Results (Points) Using an Egalitarian Perspective in the Eco-Indicator 99 Method of Impact Assessment

Impact category	Wood frame house				
	Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Total	9.9E+04	1.0E+05	1.2E+05	1.1E+05	1.2E+05
Carcinogens	4.6E+02	4.8E+02	5.3E+02	4.8E+02	5.2E+02
Respiratory organics	2.8E+01	2.9E+01	3.2E+01	2.9E+01	3.1E+01
Respiratory inorganics	2.1E+04	2.3E+04	2.3E+04	2.0E+04	2.0E+04
Climate change	7.0E+03	7.3E+03	8.6E+03	7.7E+03	8.7E+03
Radiation	1.6E+01	1.5E+01	2.2E+01	2.1E+01	2.6E+01
Ozone layer	2.7E+00	2.6E+00	3.6E+00	3.4E+00	4.2E+00
Ecotoxicity	5.7E+02	5.7E+02	6.7E+02	6.2E+02	6.9E+02
Acidification/eutrophication	3.3E+03	3.6E+03	3.6E+03	3.1E+03	3.1E+03
Land use	3.1E+02	2.9E+02	4.2E+02	4.1E+02	5.0E+02
Minerals	3.4E+02	3.3E+02	4.2E+02	4.1E+02	4.7E+02
Fossil fuels	6.6E+04	6.8E+04	8.3E+04	7.5E+04	8.7E+04
Impact category	**CMU house**				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	1.0E+05	1.0E+05	1.2E+05	1.1E+05	1.3E+05
Carcinogens	4.7E+02	4.7E+02	5.2E+02	4.8E+02	5.4E+02
Respiratory organics	2.8E+01	2.8E+01	3.1E+01	2.8E+01	3.1E+01
Respiratory inorganics	2.2E+04	2.3E+04	2.3E+04	2.0E+04	2.0E+04
Climate change	7.2E+03	7.1E+03	8.3E+03	7.7E+03	9.0E+03
Radiation	1.6E+01	1.4E+01	2.1E+01	2.1E+01	2.7E+01
Ozone layer	2.7E+00	2.5E+00	3.4E+00	3.5E+00	4.4E+00
Ecotoxicity	5.7E+02	5.6E+02	6.4E+02	6.3E+02	7.1E+02
Acidification/eutrophication	3.4E+03	3.6E+03	3.5E+03	3.0E+03	3.1E+03
Land use	3.1E+02	2.8E+02	4.0E+02	4.2E+02	5.2E+02
Minerals	3.4E+02	3.2E+02	4.0E+02	4.2E+02	4.9E+02
Fossil fuels	6.7E+04	6.5E+04	8.0E+04	7.6E+04	9.0E+04
Impact category	**CMU house compared to wood frame house****				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	-2%	2%	3%	0%	-3%
Carcinogens	-3%	2%	3%	0%	-3%
Respiratory organics	-2%	2%	3%	2%	-2%
Respiratory inorganics	-4%	-1%	1%	1%	-2%
Climate change	-2%	3%	4%	0%	-4%
Radiation	1%	7%	6%	-2%	-5%
Ozone layer	0%	6%	5%	-2%	-5%
Ecotoxicity	-1%	3%	3%	0%	-2%
Acidification/eutrophication	-3%	0%	2%	2%	-1%
Land use	0%	6%	5%	-2%	-5%
Minerals	0%	3%	3%	-2%	-4%
Fossil fuels	-1%	4%	4%	0%	-4%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. ELU is environmental load unit.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table C-2. Normalized and Weighted LCA Results (Points) Using a Hierarchic Perspective in the Eco-Indicator 99 Method of Impact Assessment

Impact category*	Wood frame house				
	Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Total	1.1E+05	1.1E+05	1.4E+05	1.3E+05	1.5E+05
Carcinogens	4.6E+02	4.8E+02	5.4E+02	4.8E+02	5.4E+02
Respiratory organics	2.8E+01	2.9E+01	3.2E+01	2.9E+01	3.1E+01
Respiratory inorganics	2.1E+04	2.3E+04	2.3E+04	2.0E+04	2.0E+04
Climate change	7.0E+03	7.4E+03	8.7E+03	7.8E+03	8.8E+03
Radiation	1.6E+01	1.5E+01	2.2E+01	2.1E+01	2.6E+01
Ozone layer	2.7E+00	2.6E+00	3.7E+00	3.4E+00	4.2E+00
Ecotoxicity	4.5E+02	4.6E+02	5.3E+02	5.0E+02	5.5E+02
Acidification/ Eutrophication	2.6E+03	2.9E+03	2.9E+03	2.5E+03	2.5E+03
Land use	2.5E+02	2.3E+02	3.4E+02	3.2E+02	4.0E+02
Minerals	3.6E+02	3.5E+02	4.4E+02	4.3E+02	5.0E+02
Fossil fuels	7.7E+04	7.6E+04	1.1E+05	9.8E+04	1.2E+05
Impact category	**CMU house**				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	1.1E+05	1.1E+05	1.4E+05	1.3E+05	1.6E+05
Carcinogens	4.7E+02	4.8E+02	5.2E+02	4.9E+02	5.5E+02
Respiratory organics	2.8E+01	2.9E+01	3.1E+01	2.8E+01	3.2E+01
Respiratory inorganics	2.2E+04	2.4E+04	2.3E+04	2.0E+04	2.0E+04
Climate change	7.2E+03	7.2E+03	8.4E+03	7.8E+03	9.2E+03
Radiation	1.6E+01	1.4E+01	2.1E+01	2.2E+01	2.8E+01
Ozone layer	2.7E+00	2.5E+00	3.5E+00	3.5E+00	4.4E+00
Ecotoxicity	4.6E+02	4.5E+02	5.2E+02	5.0E+02	5.7E+02
Acidification/eutrophication	2.7E+03	2.9E+03	2.8E+03	2.4E+03	2.5E+03
Land use	2.5E+02	2.2E+02	3.2E+02	3.3E+02	4.2E+02
Minerals	3.6E+02	3.4E+02	4.3E+02	4.4E+02	5.2E+02
Fossil fuels	7.8E+04	7.2E+04	1.0E+05	1.0E+05	1.3E+05
Impact category	**CMU house compared to wood frame house****				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	-2%	4%	4%	-1%	-4%
Carcinogens	-3%	2%	3%	0%	-3%
Respiratory organics	-2%	2%	3%	2%	-2%
Respiratory inorganics	-4%	-1%	1%	1%	-2%
Climate change	-2%	3%	4%	0%	-4%
Radiation	1%	7%	6%	-2%	-5%
Ozone layer	0%	6%	5%	-2%	-5%
Ecotoxicity	-1%	3%	3%	0%	-2%
Acidification/eutrophication	-3%	0%	2%	2%	-1%
Land use	0%	6%	5%	-2%	-5%
Minerals	0%	3%	3%	-2%	-4%
Fossil fuels	-1%	6%	5%	-2%	-5%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. ELU is environmental load unit.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table C-3. Normalized and Weighted LCA Results (Points) Using an Individualist Perspective in the Eco-Indicator 99 Method of Impact Assessment

Impact category*	Wood frame house				
	Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Total	7.4E+04	7.8E+04	8.5E+04	7.6E+04	8.2E+04
Carcinogens	6.1E+02	6.4E+02	7.1E+02	6.3E+02	6.9E+02
Respiratory organics	8.8E+01	9.3E+01	1.0E+02	9.1E+01	9.9E+01
Respiratory inorganics	3.4E+04	3.8E+04	3.7E+04	3.2E+04	3.2E+04
Climate change	2.3E+04	2.4E+04	2.8E+04	2.5E+04	2.9E+04
Radiation	2.5E+00	2.4E+00	3.3E+00	3.2E+00	3.9E+00
Ozone layer	7.4E+00	7.2E+00	1.0E+01	9.5E+00	1.2E+01
Ecotoxicity	4.1E+01	4.1E+01	4.8E+01	4.5E+01	5.0E+01
Acidification/eutrophication	1.9E+03	2.0E+03	2.0E+03	1.8E+03	1.8E+03
Land use	1.8E+02	1.7E+02	2.4E+02	2.3E+02	2.8E+02
Minerals	1.4E+04	1.3E+04	1.7E+04	1.6E+04	1.9E+04
Impact category	**CMU house**				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	7.6E+04	7.7E+04	8.3E+04	7.6E+04	8.4E+04
Carcinogens	6.2E+02	6.3E+02	6.8E+02	6.2E+02	7.0E+02
Respiratory organics	8.9E+01	9.1E+01	9.9E+01	9.0E+01	1.0E+02
Respiratory inorganics	3.6E+04	3.8E+04	3.7E+04	3.2E+04	3.2E+04
Climate change	2.3E+04	2.3E+04	2.7E+04	2.5E+04	3.0E+04
Radiation	2.5E+00	2.2E+00	3.1E+00	3.3E+00	4.1E+00
Ozone layer	7.4E+00	6.8E+00	9.5E+00	9.7E+00	1.2E+01
Ecotoxicity	4.1E+01	4.0E+01	4.7E+01	4.5E+01	5.2E+01
Acidification/eutrophication	1.9E+03	2.0E+03	2.0E+03	1.7E+03	1.8E+03
Land use	1.8E+02	1.6E+02	2.3E+02	2.4E+02	3.0E+02
Minerals	1.4E+04	1.3E+04	1.6E+04	1.7E+04	1.9E+04
Impact category	**CMU house compared to wood frame house****				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	-3%	1%	2%	0%	-3%
Carcinogens	-1%	3%	4%	2%	-2%
Respiratory organics	-2%	2%	3%	2%	-2%
Respiratory inorganics	-4%	-1%	0%	1%	-2%
Climate change	-2%	3%	4%	0%	-4%
Radiation	1%	7%	5%	-2%	-4%
Ozone layer	0%	6%	5%	-2%	-5%
Ecotoxicity	-1%	4%	4%	0%	-3%
Acidification/eutrophication	-3%	0%	2%	2%	-1%
Land use	0%	6%	5%	-2%	-5%
Minerals	0%	3%	3%	-2%	-4%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. ELU is environmental load unit.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table C-4. Normalized and Weighted LCA Results (Points) Using the EDIP/UMIP 97 Method of Impact Assessment

Impact category*	Wood frame house				
	Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Total	2.7E+03	2.8E+03	3.5E+03	3.2E+03	3.8E+03
Global warming (GWP 100)	2.6E+02	2.7E+02	3.2E+02	2.9E+02	3.2E+02
Ozone depletion	1.5E+01	1.5E+01	2.0E+01	1.9E+01	2.3E+01
Acidification	1.2E+02	1.3E+02	1.3E+02	1.1E+02	1.1E+02
Eutrophication	2.4E+01	2.6E+01	2.7E+01	2.3E+01	2.3E+01
Photochemical smog	3.1E+01	3.2E+01	3.6E+01	3.3E+01	3.6E+01
Ecotoxicity water chronic	4.5E+02	4.6E+02	5.4E+02	5.0E+02	5.6E+02
Ecotoxicity water acute	4.6E+02	4.7E+02	5.6E+02	5.2E+02	5.9E+02
Ecotoxicity soil chronic	1.9E+02	1.8E+02	2.8E+02	2.7E+02	3.4E+02
Human toxicity air	5.0E+01	5.0E+01	6.2E+01	5.9E+01	6.8E+01
Human toxicity water	2.0E+02	2.2E+02	2.3E+02	2.1E+02	2.3E+02
Human toxicity soil	6.2E+02	6.0E+02	8.9E+02	8.5E+02	1.1E+03
Bulk waste	1.6E+02	1.7E+02	1.6E+02	1.4E+02	1.4E+02
Hazardous waste	3.0E+00	3.0E+00	3.4E+00	3.4E+00	3.7E+00
Radioactive waste	1.3E+02	1.3E+02	2.0E+02	1.9E+02	2.5E+02
Slags/ashes	1.1E-01	1.1E-01	1.3E-01	1.3E-01	1.4E-01
Impact category	**CMU house**				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	2.8E+03	2.7E+03	3.4E+03	3.3E+03	3.9E+03
Global warming (GWP 100)	2.7E+02	2.6E+02	3.1E+02	2.9E+02	3.4E+02
Ozone depletion	1.5E+01	1.4E+01	1.9E+01	1.9E+01	2.4E+01
Acidification	1.3E+02	1.3E+02	1.3E+02	1.1E+02	1.1E+02
Eutrophication	2.5E+01	2.6E+01	2.6E+01	2.3E+01	2.4E+01
Photochemical smog	3.1E+01	3.1E+01	3.5E+01	3.2E+01	3.7E+01
Ecotoxicity water chronic	4.7E+02	4.6E+02	5.3E+02	5.1E+02	5.8E+02
Ecotoxicity water acute	4.7E+02	4.6E+02	5.5E+02	5.3E+02	6.2E+02
Ecotoxicity soil chronic	1.9E+02	1.7E+02	2.6E+02	2.8E+02	3.6E+02
Human toxicity air	5.1E+01	4.8E+01	6.0E+01	6.0E+01	7.0E+01
Human toxicity water	2.3E+02	2.4E+02	2.5E+02	2.3E+02	2.5E+02
Human toxicity soil	6.3E+02	5.5E+02	8.4E+02	8.7E+02	1.1E+03
Bulk waste	1.6E+02	1.7E+02	1.6E+02	1.4E+02	1.4E+02
Hazardous waste	3.0E+00	2.9E+00	3.4E+00	3.4E+00	3.8E+00
Radioactive waste	1.3E+02	1.1E+02	1.9E+02	2.0E+02	2.7E+02
Slags/ashes	1.1E-01	1.0E-01	1.2E-01	1.2E-01	1.4E-01

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. ELU is environmental load unit.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table C-4. Normalized and Weighted LCA Results (Points) Using the EDIP/UMIP 97 Method of Impact Assessment (Continued)

Impact category	CMU house compared to wood frame house**				
	Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Total	-3%	3%	3%	-2%	-5%
Global warming (GWP 100)	-2%	3%	4%	0%	-4%
Ozone depletion	0%	6%	5%	-2%	-5%
Acidification	-2%	0%	2%	3%	0%
Eutrophication	-3%	0%	2%	2%	-2%
Photochemical smog	-1%	3%	4%	1%	-2%
Ecotoxicity water chronic	-3%	0%	1%	-2%	-5%
Ecotoxicity water acute	-2%	2%	3%	-1%	-4%
Ecotoxicity soil chronic	-1%	7%	6%	-3%	-6%
Human toxicity air	-1%	4%	4%	-1%	-4%
Human toxicity water	-14%	-10%	-8%	-10%	-13%
Human toxicity soil	0%	7%	6%	-3%	-5%
Bulk waste	-3%	0%	1%	3%	-0%
Hazardous waste	0%	2%	2%	-1%	-2%
Radioactive waste	0%	9%	7%	-3%	-6%
Slags/ashes	4%	6%	6%	3%	1%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. ELU is environmental load unit.

**Positive values indicate less impact for CMU house compared to wood frame house.

Table C-5. Normalized and Weighted LCA Results (Points) Using the EPS 2000 Method of Impact Assessment

Impact category*	Wood frame house				
	Lake Charles	Tucson	St. Louis	Denver	Minne-apolis
Total	7.1E+05	7.1E+05	9.1E+05	8.4E+05	9.9E+05
Life expectancy	1.8E+05	1.9E+05	2.2E+05	1.9E+05	2.1E+05
Severe morbidity	5.6E+04	5.8E+04	7.1E+04	6.4E+04	7.3E+04
Morbidity	1.2E+04	1.3E+04	1.5E+04	1.4E+04	1.5E+04
Severe nuisance	1.7E+03	1.7E+03	1.8E+03	1.8E+03	1.8E+03
Nuisance	6.8E+03	7.4E+03	7.3E+03	6.2E+03	6.1E+03
Crop growth capacity	7.0E+02	7.4E+02	8.2E+02	7.2E+02	7.8E+02
Wood growth capacity	-3.1E+03	-3.3E+03	-3.7E+03	-3.3E+03	-3.7E+03
Fish and meat production	-1.4E+02	-1.5E+02	-1.5E+02	-1.3E+02	-1.3E+02
Soil acidification	1.8E+02	2.0E+02	2.0E+02	1.7E+02	1.7E+02
Prod. cap. irrigation water	2.4E-01	2.4E-01	2.4E-01	2.4E-01	2.4E-01
Prod. cap. drinking water	2.4E+00	2.4E+00	2.4E+00	2.4E+00	2.4E+00
Depletion of reserves	4.5E+05	4.4E+05	6.0E+05	5.6E+05	6.8E+05
Species extinction	2.2E+03	2.3E+03	2.8E+03	2.5E+03	2.8E+03
Impact category	**CMU house**				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	7.2E+05	6.8E+05	8.7E+05	8.5E+05	1.0E+06
Life expectancy	1.9E+05	1.9E+05	2.1E+05	1.9E+05	2.2E+05
Severe morbidity	5.7E+04	5.6E+04	6.8E+04	6.4E+04	7.6E+04
Morbidity	1.3E+04	1.3E+04	1.5E+04	1.4E+04	1.6E+04
Severe nuisance	1.7E+03	1.7E+03	1.8E+03	1.8E+03	1.9E+03
Nuisance	6.9E+03	7.4E+03	7.1E+03	6.0E+03	6.1E+03
Crop growth capacity	7.2E+02	7.3E+02	8.0E+02	7.2E+02	8.0E+02
Wood growth capacity	-3.2E+03	-3.2E+03	-3.6E+03	-3.3E+03	-3.8E+03
Fish and meat production	-1.4E+02	-1.5E+02	-1.5E+02	-1.3E+02	-1.4E+02
Soil acidification	1.9E+02	2.0E+02	1.9E+02	1.6E+02	1.7E+02
Prod. cap. irrigation water	2.4E-01	2.4E-01	2.4E-01	2.4E-01	2.4E-01
Prod. cap. drinking water	2.4E+00	2.4E+00	2.4E+00	2.4E+00	2.4E+00
Depletion of reserves	4.5E+05	4.2E+05	5.7E+05	5.7E+05	7.1E+05
Species extinction	2.2E+03	2.2E+03	2.6E+03	2.5E+03	2.9E+03
Impact category	**CMU house compared to wood frame house****				
	Lake Charles	**Tucson**	**St. Louis**	**Denver**	**Minne-apolis**
Total	-1%	4%	4%	-1%	-4%
Life expectancy	-3%	1%	3%	0%	-3%
Severe morbidity	-2%	3%	4%	-1%	-4%
Morbidity	-2%	2%	3%	0%	-3%
Severe nuisance	0%	1%	1%	0%	-1%
Nuisance	-2%	0%	2%	3%	0%
Crop growth capacity	-2%	1%	3%	1%	-3%
Wood growth capacity	-2%	2%	3%	0%	-3%
Fish and meat production	-3%	0%	1%	1%	-2%
Soil acidification	-2%	0%	2%	3%	0%
Prod. cap. irrigation water	0%	0%	0%	0%	0%
Prod. cap. drinking water	0%	0%	0%	0%	0%
Depletion of reserves	-1%	5%	5%	-2%	-4%
Species extinction	-2%	3%	4%	-1%	-4%

*The notation in the table is a modified scientific notation, for example 1.2E+04 means 1.2×10^4 which is equal to 12,000. ELU is environmental load unit.

**Positive values indicate less impact for CMU house compared to wood frame house.