Title
Life-Cycle Evaluation of Concrete Building Construction as a Strategy for Sustainable Cities

Author
Stadel, Alexander

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by

Alexander Stadel[*#]
Petek Gursel[*+]
Eric Masanet[*i]

Principal Investigator:
Eric Masanet

18-January-2012

[*] Lawrence Berkeley National Laboratory
[#] Drexel University
[+] University of California, Berkeley

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KEYWORDS

Life cycle assessment, structural materials, environmental impacts, commercial buildings, modeling

ABSTRACT

Structural materials in commercial buildings in the United States account for a significant fraction of national energy use, resource consumption, and greenhouse gas (GHG) emissions. Robust decisions for balancing and minimizing these various environmental effects require that structural materials selections follow a life-cycle, systems modeling approach. This report provides a concise overview of the development and use of a new life-cycle assessment (LCA) model for structural materials in U.S. commercial buildings—the Berkeley Lab Building Materials Pathways (B-PATH) model. B-PATH aims to enhance environmental decision-making in the commercial building LCA, design, and planning communities through the following key features: (1) Modeling of discrete technology options in the production, transportation, construction, and end of life processes associated U.S. structural building materials; (2) Modeling of energy supply options for electricity provision and directly combusted fuels across the building life cycle; (3) Comprehensiveness of relevant building mass and energy flows and environmental indicators; (4) Ability to estimate modeling uncertainties through easy creation of different life-cycle technology and energy supply pathways for structural materials; and (5) Encapsulation of the above features in a transparent public use model. The report summarizes literature review findings, methods development, model use, and recommendations for future work in the area of LCA for commercial buildings.

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1. INTRODUCTION

1.1. Background

Commercial buildings in the United States account for a significant fraction of national energy use, resource consumption, and greenhouse gas (GHG) emissions. In 2009, commercial buildings accounted for nearly 20% of U.S. primary energy use, over one-third of U.S. electricity use, and about 15% of U.S. (direct) natural gas use (U.S. DOE 2010). The GHG emissions associated with this energy use amounted to roughly 1 billion metric tons of carbon dioxide equivalents (Mg CO_2e) in 2009, or 20% of U.S. total energy-related GHG emissions (U.S. DOE 2011). The air pollution and human health implications of this energy use are also significant. Based on data from the National Research Council (NRC 2010), the human health damages associated with the amounts of electricity and natural gas consumed by U.S. commercial buildings may be on the order of $20 billion per year.

However, the environmental impacts associated with commercial buildings are not limited to their operational energy use impacts. There are over 4.6 million commercial buildings in the United States, which encompass over 64 billion square feet (ft^2) of floor space (U.S. DOE 2006). Each of these buildings requires the production and transportation of many tons of energy-intensive raw materials such as steel, glass, concrete, aluminum, and lumber in their construction and maintenance. Although a coarse estimate, if one assumes a combined, average embodied GHG emissions intensity of 40 lb CO_2e/ft^2 for these building materials (Ochsendorf et al. 2011), the cumulative embodied emissions associated with today's commercial floor space would amount to another 1 billion Mg CO_2e.

Green design strategies that seek to minimize the environmental impacts of a building throughout its entire life cycle (i.e., from "cradle to grave") may thus hold significant potential for reducing environmental impacts in the United States. The cornerstone of such strategies is an analytical approach known as life-cycle assessment (LCA). An LCA employs data analysis and systems mass and energy balance modeling techniques to estimate the inputs of fuels, materials, and resources—and outputs of pollutants and waste—associated with all relevant processes in the life cycle of a product or service. Increasingly, LCA data and approaches are being applied to green design tools and rating schemes for buildings. Examples include the National Institute of Standards and Technology's Building for Environmental and Economic Sustainability (BEES) software (NIST 2011) and the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) building rating system (USGBS 2011).

In green design efforts for commercial buildings, choices for structural materials are of particular importance for several reasons. First, structural frames typically account for the largest mass fraction of energy-intensive materials in a building, and therefore offer a key opportunity for managing the embodied impacts of building materials. Second, the amounts and types of structural materials are key determinants of a building's thermal mass, which can have a significant influence on the operating energy use of a building's heating and cooling systems in certain climates (Marceau and VanGeem 2007). Third, given their large share of a building's mass, structural materials can generate large amounts of solid waste at the construction and end of life phases. For example, in 1996 an estimated 78 million tons of construction and demolition

(C&D) waste in the United States were attributable to commercial buildings, of which only 20-30% was recovered for processing and recycling (Franklin Associates 1998). Structural materials choices that improve materials recycling and reuse opportunities can thus play a key role in reducing U.S. solid waste generation, and the associated environmental impacts that come along with waste handling and disposal. Robust decisions for balancing and minimizing these various environmental effects require that structural materials selections follow a life-cycle, systems modeling approach.

1.2. Project Scope

This report provides a concise overview of the development and use of a new LCA model for structural materials in U.S. commercial buildings. Developed by researchers at Lawrence Berkeley National Laboratory (LBNL), the Berkeley Lab Building Materials Pathways (B-PATH) Model aims to enhance environmental decision-making in the commercial building LCA, design, and planning communities through the following key features:

1. ***Modeling of discrete technology options*** in the production, transportation, construction, and end of life processes associated U.S. structural building materials. While there have been a number of stand-alone LCAs of commercial buildings and their materials, it is often difficult to transfer the results of these studies to assessments of real-world buildings. Specifically, the environmental impacts of structural materials for a given job site will depend in part on the technology characteristics of local and regional supply chains; these characteristics might differ from the "average" technology assumptions used in many building LCA studies and databases.
2. ***Modeling of energy supply options*** for electricity provision and directly combusted fuels across the building life cycle. Most LCA models allow for some user-defined energy supply assumptions. However, often the LCI data in such models are not sufficiently disaggregated into unit process technologies, whose energy use and fuel options (e.g., alternative fuels or fuel switching) can vary in practice. B-PATH allows for user-defined energy supply at the process technology level, which provides greater flexibility for modeling regional and production system energy supply variations for structural materials.
3. ***Comprehensiveness*** of relevant building mass and energy flows and environmental indicators to ensure that B-PATH's discrete technology modeling approach allows for consideration of a range of environmental impacts in materials selection, and for different building elements.
4. ***Ability to estimate modeling uncertainties*** through easy creation of different life-cycle technology and energy supply pathways for structural materials, and easy consideration of different methodological assumptions (e.g., system boundaries and allocation protocols), which can serve as bounding scenarios on environmental impacts.
5. Encapsulation of the above features in a transparent ***public use model***, which can be assessed and refined by the stakeholder community, expanded to include new technology options as they emerge over time, and can offer a fully citable public data resource.

Model development was focused on life-cycle pathways for three major structural materials options for commercial buildings: (1) reinforced concrete; (2) steel; and (3) lumber.

The current version of B-PATH is targeted at low-rise construction (typically defined as 2-5 floors) due to the predominance of this building form in the U.S. commercial sector.

1.3. Report Structure

This report is designed to be a concise reference to accompany the B-PATH model. Its purpose is to provide brief descriptions of the model's methodological positioning, features, and architecture, as well as an overview of how the model can be used. The B-PATH model file contains citations to all data sources as well as a comprehensive reference list. Readers are referred to the model itself to review data values and sources for key modeling parameters.

The first step in the development of B-PATH was a comprehensive review of literature and public information sources relevant to LCA of commercial buildings and their structural materials. The review had two primary goals. First, it focused on identifying credible sources of public data for modeling of key processes and technology options in the commercial building life cycle. Second, it aimed to assess the body of relevant work to identify both data gaps and opportunities for enhanced decision making through new modeling approaches. (This latter goal resulted in the "key features" of B-PATH described in the previous section.) To keep the main body of this report concise, summaries of the literature review findings for concrete, wood, and steel are provided in Appendix A.

Chapter 2 provides a brief overview of B-PATH's main methodological features, with specific references to the model's architecture and data elements that enable each feature.

Chapter 3 offers a concise tour of B-PATH's major data and modeling modules. This information is meant to serve as a brief user's reference to B-PATH; as such, it summarizes each modeling module, the major process steps and technology options contained within them, and the key user inputs that are required. Chapter 3 also contains schematics of B-PATH's module and process architectures to help orient the user on the model's structure.

Chapter 4 describes a case study application of B-PATH to illustrate its capabilities for modeling technology variations and regional scenarios. The case study compares the environmental performance of different structural materials options for a prototypical low-rise commercial building in California, and considers how different materials pathway assumptions might affect these comparisons.

Lastly, Chapter 5 summarizes areas of future work to improve the B-PATH model, its data sources, and its utility as a public resource for assessing the environmental performance of U.S. commercial buildings.

2. METHODOLOGICAL APPROACH

A credible LCA of commercial buildings requires many data—and many modeling assumptions—to characterize the myriad flows of mass and energy that occur across a building's life cycle, and the various environmental impacts that are attributable to these flows. A number of previous studies have produced comprehensive building LCAs (see Appendix A). Furthermore, there are several public (e.g., BEES) and commercial (e.g., Athena's Impact Estimator) databases and software tools that can be employed to perform partial and full building LCAs. Often these existing databases and tools provide results that are robust and appropriate for different building design and planning decisions.

The goal of the B-PATH model is not to supplant these available studies and tools. Rather, the intent is to provide a complementary public resource that builds upon the best available data, modeling approaches, and insights that have been generated from such studies and tools, and to offer several methodological features that address areas of opportunity for enhanced building LCA. Furthermore, as a public resource, B-PATH's results and data sources are fully citable, its calculation methodology is transparent (for replication and scrutiny), and its functionality can be refined and improved by others over time.

This chapter provides a brief overview of key methodological features of B-PATH, which are meant to improve the flexibility and utility of LCA for building designers, planners, and environmental analysts. For more detail on the data sources and modeling structures associated with each feature, the reader is referred to the B-PATH model.

2.1. Technology Options

A distinguishing feature of the B-PATH model is that it takes a "bottom up," unit process based approach to modeling the life-cycle inventories (LCIs) of structural materials. This approach allows the user to create different "cradle to gate" technology scenarios for the production of structural building materials, and therefore to model variations in production pathways that can occur due to supply chain configurations, geographical locations of plants, plant technology vintages, fuel mixes, logistics, and other materials pathway characteristics that can be unique to local and regional supply chains.

This functionality addresses some common analysis challenges that are encountered when performing a building LCA:

- Many LCI data in the public domain are reported only on an aggregate basis—e.g., the cumulative energy demand of a ton of cement—without sufficient detail on the technology, process, and regional assumptions that are associated with the data. Thus, the analyst cannot properly assess the suitability of the LCI data for his or her system of study, nor can he or she disaggregate the data to change key assumptions to better model the system of study.
- Many LCI data in the public domain are reported on a national average basis, which may not be credible for local and regional materials pathways that differ significantly from national average conditions. For example, cement plants in California are among the most energy efficient in the nation (CalTrans 2011). Since cement is largely a local commodity, cement

purchased for a building project in Los Angeles is likely to have lower per-ton environmental impacts than the national average.
- LCI data in the public domain emerge slowly, and thus do not often represent current or emerging technologies along the materials supply chain. Thus, the analyst is often using old data to guide today's (and, increasingly, tomorrow's) decisions. This time lag poses a particular problem when designers and planners look to LCA to help guide "green purchasing" decisions, since current or cutting-edge supply chain technologies are not typically represented in their analyses.
- Many LCA analysts do not have sufficient understanding of (often arcane) process and technology variations for the manufacture of materials, and thus lack the ability to confidently alter available LCI data if such data can be easily disaggregated.

B-PATH models materials pathways as a collection of major process steps, which can each be modified by changing key process technology assumptions. The technology options include both current and best practice technologies for a number of processes. This built-in process granularity and technology representation allows for modeling of supply chain characteristics (or possibilities) that are relevant to local decision making. As new technologies emerge, they can be added as options within the appropriate process step.

All best practice LCI values (with citations) can be reviewed on the relevant B-PATH worksheet

Table 2-1, Table 2-2, and **Error! Reference source not found.** summarize the major process steps in B-PATH's concrete, lumber, and steel production modules. For further details, the reader is referred to the individual process worksheets in the B-PATH model. The labels in the first column of each table refer to individual process worksheets in the model.

Discrete technology options are provided for the concrete and lumber pathway processes, given that the production flow for these materials is linear and unit process technologies can be (mostly) mixed and matched in practice. For steel, given the complexity and interdependencies of processes, and the circularity of material flows in the economy, representative "best practice" technology options are available for each process. These best practice options represent a combination of discrete technologies that have been verified in practice for a particular process step, and for which resource and material requirements could be established from the literature. For example, best practice coking represents a modern coke plant using standard technology, including electrical exhausters, high-pressure ammonia liquor spray for oven aspiration, as well as variable speed drives on motors and fans (Worrell et al. 2007). All best practice LCI values (with citations) can be reviewed on the relevant B-PATH worksheet.

Table 2-1. Processes and Technologies in the Concrete Module

Concrete Module	Process	Options
Cement Production		
C_Raw Meal	Quarrying	
	Raw Materials Prehomogenization	Raw storing, non-preblending
		Raw storing, preblending
	Raw Materials Grinding	Dry raw grinding, ball mill
		Dry raw grinding, tube mill
		Dry raw grinding, vertical roller mill
		Wet raw grinding, tube mill
		Wet raw grinding, wash mill
	Raw Blending/ Homogenization	Raw meal homogenization, blending, and storage
		Slurry blending homogenization and storage
C_Pyroprocess	Fuels Preparation	
	Pyroprocessing	Wet kiln
		Long dry kiln
		Preheater kiln
		Preheater/Precalciner kiln
		U.S. Average kiln
C_Clinker Cooling	Clinker Cooling	Rotary (Tube) Cooler
		Planetary (Satellite) Cooler
		Reciprocating Grate Cooler
	Emissions Control	Fabric Filter
		Electrostatic Precipitators (ESP)
C_Finish Mill Grind	Cement Finish Milling and Grinding	Tube Mill
		Vertical Roller Mill
		Ball Mill
		Roller Press
		Horizontal Roller Mill (Horomill)
C_SCM	SCM (and Additives) Preparation and Grinding with PC	Traditional Portland cement, Type I-V
		Blended cements_Portland blast furnace slag cement,Type IS
		Blended cements_Slag modified Portland cement,Type I[SM]
		Blended cements_Slag cement ,Type S
		Blended cements_Portland pozzolan cement,Type IP/P
		Blended cements_Pozzolan-modified Portland cement,Type I[PM]
		Portland cement with recycled CKD
		Portland cement with carbon sequestration in CKD
Aggregates	Aggregates productions	Sand and gravel

Production		
		Crushed stone
Admixtures Production	Chemical admixtures production	Plasticiser
		Superplasticiser
		Retarder
		Accelerating admixture
		Air entraining admixture
		Waterproofing admixture
Concrete Production	Concrete mixing and batching	Transit Mixed Concrete (dry batch process)
		Shrink Mixed Concrete (half wet batch process)
		Central Mixed Concrete (wet batch process)

Table 2-2. Processes and Technology Options in the Steel Module

Steel Module	Process	Options
Mining		
S_Mining	Ore mining	U.S. average mining practices
		Best practice energy efficient mining equipment
Liquid Steel Production		
S_Sinter	Sintering	U.S. average sintering
		Best practice sintering efficiency
S_Pellet	Pelleting	U.S. average sintering
		Best practice pelleting efficiency
S_Coking	Coking	U.S. average coking
		Best practice coking efficiency
S_Blast_Furnace	Blast furnace	U.S. average blast furnace
		Best practice blast furnace
S_BOF	Basic oxygen furnace	U.S. average BOF
		Best practice BOF efficiency
S_DRI	Direct reduced iron	World average DRI
		Best practice DRI efficiency
S_Scrap	Scrap recovery	U.S. average scrap recovery
S_DRI_EAF	DRI electric arc furnace	World average DRI EAF
		Best practice DRI EAF efficiency
S_R_EAF	Scrap electric arc furnace	U.S. average EAF
		Best practice EAF efficiency
S_Liquid_Mix		Allows for specification of mix of liquid steel based on percent from blast furnace-BOF route, DRI-EAF route, and scrap-EAF route to assess different ratios of virgin to recycled steel, and different technologies for producing virgin and recycled steel
S_Casting	Casting	U.S. average continuous casting
		Best practice continuous casting
		Ladle metallurgy

S_Reheat	Reheat furnace	U.S. average reheat furnace
		Best practice reheat furnace efficiency
S_Forming	Rolling and finishing	U.S. average hot rolling
		Best practice rolling efficiency

Table 2-3. Processes and Technologies in the Lumber Module

Lumber Module	Process	Options
W_Silviculture	Silviculture	Planting Density (865, 1235m 1729 TPH)
		Site Prep- Fertilizer, Herbicide, and Pre-Commercial Thinning and Commercial Thinning Options
W_Sawing	Sawing	Region: Pacific Northwest, Southeast, Northeast, or Inland Northwest
		Species: Douglas Fir, Hemlock, Southern Pine, Pine, Spruce, Fir, Larch, or Red Cedar
W_Boilers	Boilers for Kiln Drying	Natural Gas_Large Wall-Fired Boilers (>100 MMBtu/hr Heat Input)_Uncontrolled (Pre-NSPS)
		Natural Gas_Large Wall-Fired Boilers (>100 MMBtu/hr Heat Input)_Uncontrolled (Post-NSPS)
		Natural Gas_Large Wall-Fired Boilers (>100 MMBtu/hr Heat Input)_Controlled - Low NOx burners
		Natural Gas_Large Wall-Fired Boilers (>100 MMBtu/hr Heat Input)_Controlled - Flue gas recirculation
		Natural Gas_Small Boilers (<100 MMBtu/hr Heat Input)_Uncontrolled
		Natural Gas_Small Boilers (<100 MMBtu/hr Heat Input)_Controlled - Low NOx burners
		Natural Gas_Small Boilers (<100 MMBtu/hr Heat Input)_Controlled - Low NOx burners/Flue gas recirculation
		Natural Gas_Tangential-Fired Boilers (All Sizes)_Uncontrolled
		Natural Gas_Tangential-Fired Boilers (All Sizes)_Controlled - Flue gas recirculation
		Wood_Dutch oven
		Wood_spreader stoker
		Wood_fuel cell oven
		Wood_fluidized bed combustion boiler
		LPG_Butane Industrial Boiler
		LPG_Propane Industrial Boiler
		LPG_Butane Industrial Boiler_Low NOx
		LPG_Propane Industrial Boiler_ Low Nox
		Boilers > 100 Million Btu/hr_No. 2 oil fired
		Boilers < 100 Million Btu/hr_Distillate oil fired
W_Kiln Drying		Region: Pacific Northwest, Southeast, Northeast, or Inland Northwest
		Species: Douglas Fir, Hemlock, Southern Pine, Pine, Spruce, Fir, Larch, or Red Cedar
W_Planing		Region: Pacific Northwest, Southeast, Northeast, or Inland

		Northwest
		Species: Douglas Fir, Hemlock, Southern Pine, Pine, Spruce, Fir, Larch, or Red Cedar
W_Allocation		Same boilers are available as in the W_Boiler Module, but for the exclusive burning of wood co-products for energy

2.2. Regionalization

The B-PATH model allows for tailoring analyses to specific geographic regions across the building life cycle in three different ways:

1. For discrete processes: Users can specify the fuel and technology characteristics of each process, which allows for modeling of local and regional characteristics in materials supply chains, construction practices, and end of life pathways. For example, for a building located in California, the user can select technology options and fuel mixes that are representative of California cement plants (e.g., a dry kiln with precalciner/preheater, partially fired with waste fuels). Or, when California cement imports are a possibility, technology and fuel mix options that are representative of imported cement (e.g., vertical shaft or wet kilns fired with coal in China).
2. For regional electrical power and water supply systems: Users can specify the local mix of electrical power supply, as well as the region of water withdrawals for discrete processes. B-PATH contains default values for electricity generation by state from the U.S. Environmental Protection Agency's eGRID database, and further allows users to create custom electricity generation mixes. The model also contains default values by state for the energy and emissions intensity of plant water consumption.
3. For operational energy use: B-PATH contains default values for operational energy use by U.S. climate zone, which account for the thermal mass effects of different structural material designs in different climate zones. The user can adjust the assumptions for energy use and thermal mass effects. Alternatively, the user can input results from whole building energy simulations (e.g.., from EnergyPlus) for greater accuracy.

Default values have been provided in B-PATH based on best available data sources identified by the research team. However, all data inputs and technology options can be adjusted by the user at his or her discretion, and can be updated in future versions of B-PATH as better public data emerge.

2.3. Comprehensiveness

As discussed in Chapter 1, the choice of structural material has environmental implications across all stages of the building life cycle. Thus, the model allows for assessment of impacts and tradeoffs by life cycle stage. B-PATH divides the life cycle into four primary stages: raw materials production and transport, building construction, building operations and maintenance, and end of life. Further details on the life cycle stage architecture of B-PATH are provided in Chapter 3.

B-PATH is intended for estimating both the differences in life-cycle impacts between structural materials choices and the absolute life-cycle impacts of an individual building. Thus, the model also includes “balance of building” materials and building elements, which are listed in **Error! Reference source not found.**. The balance of building data cover materials and elements that are either common to all building types (e.g., copper tubing and wire, carpet tiles) or can vary in quantities between building types (e.g., fire retardant and insulation). The balance of building materials and elements are modeled using best available LCI data in aggregate fashion (i.e., they are not disaggregated by process step) given that the focus of the current version of B-PATH is on structural materials pathways. LCI data sources for balance of building materials and elements are provided in the B-PATH model.

Table 2-4. Balance of Building Elements

Acrylic Rubber - Waterproofing
Aluminum-Doors, Frames
Aluminum-Panels
Carpet Tile
Ceramic Tile
Copper - Tubing, Wire
Elevator
Emergency generator
Epoxy Grout
Fire Retardant
Glass
Glass Fiber
Gypsum board
HVAC multi-zone units
Insulation - Extrud. Polystyrene
Insulation - Fiberglass
Paint
Plaster
Plywood
Polyethylene Sealant
Polypropylene - Piping
PVC-Waterstop
Resilient Flooring
Steel - Metal stairs
Steel - studs, doors, frames, grid
Switchgear
Water heater
Wood-Doors, Frames
Wood-Flooring

A key goal in the development of B-PATH was to include as many LCI energy and mass flows and LCIA impact categories as could be credibly modeled using publicly-available data. **Error! Reference source not found.** lists the LCI and LCIA scope of the current model. Due to data limitations, the LCI coverage varies slightly across processes and technologies; data gaps can be identified by worksheet in the B-PATH model. Where possible, the research team addressed key LCI data gaps in the pathways for steel, concrete, and lumber by estimating mass and energy flows from the process engineering and energy analysis literatures. In such instances, citations are provided in the B-PATH model. For LCIA, TRACI was chosen as the indicator model given that it is the most robust set of indicators developed for the United States.

Table 2-5. B-PATH LCI and LCIA Categories

Life-cycle inventory (mass/energy flows)
Total Primary Energy Consumption (MJ)
Electricity Consumption (kWh)
Fossil fuel Consumption (MJ) (16 types)
Non fossil fuel consumption (MJ) (3 types)
Biogenic fuel consumption (MJ)
Water Consumption (m3)
Solid Waste (kg)
Air Emissions (~100 types)
Water Emissions (~90 types)
Life-cycle impact (TRACI)
Acidification-air
Ecotoxicity-air
Ecotoxicity-water
Eutrophication-air
Eutrophication-water
GlobalWarming-air
HumanHealthCancer-air
HumanHealthCancer-water
HumanHealthNoncancer-air
HumanHealthNoncancer-water
HumanHealthCriteria
OzoneDepletion-air
PhotochemicalSmog-air
Life-cycle impact (other)
Total Primary Energy Consumption (MJ)

2.4. Uncertainty Estimation

By design, B-PATH facilitates assessment of modeling uncertainties, which are defined as uncertainties related to differences in process pathway assumptions and calculation strategies between modeling scenarios. Users can readily vary system boundaries by including or excluding specific life-cycle stages and processes, technology and fuel mix assumptions for different processes and stages, LCI allocation schemes by adjusting key allocation decisions for different materials and end of life pathways, and the building lifespan.

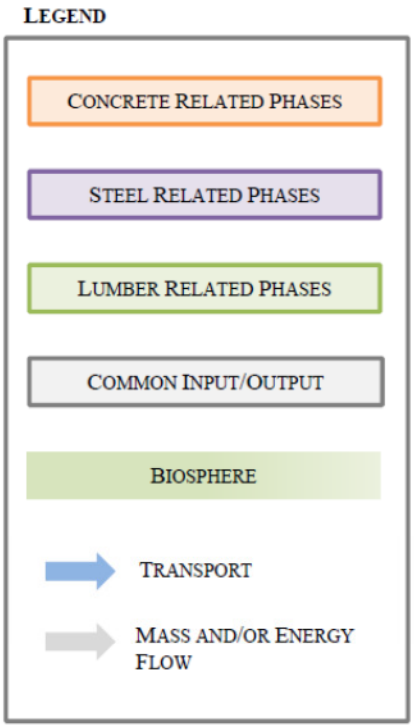
As such, the model allows the user to create different plausible scenarios for the life-cycle system. These scenarios can be used to compare how results and conclusions may differ under different system assumptions, and to assess how different methodological decisions (e.g., the choice of systems boundaries or allocation procedures) might influence the results. Bounding scenarios can also be created to estimate minimum and maximum cases for different energy and mass flows and environmental impact (e.g., through best and worst case technology assumptions).

An example scenario analysis is provided in the case study in Chapter 4.

The B-PATH model does not include estimates of parameter uncertainty, which are defined as the uncertainties related to individual data inputs in the model (e.g., the error range on the mass quantity of coal necessary to produce a ton of coke). The inclusion of parameter uncertainty estimates was beyond the project's scope and budget, and robust estimates of parameter uncertainty are lacking for many LCI data in the public domain. However, since B-PATH is a Microsoft Excel-based model, it is compatible with software packages (e.g.,, Oracle's Crystal Ball or Palisade's @RISK) that can perform sensitivity and parameter uncertainty analyses (based on user inputs) using Excel-based models.

3. OVERVIEW OF THE B-PATH MODEL

The architecture of the B-PATH model is illustrated schematically in Figure 3-1 through Figure 3-4 (legend shown below) and in Table 3-1 through Table 3-10. The spreadsheet based model uses individual worksheets (tabs) to organize data and calculations. All user input is completed by filling out the yellow cells in the 'Input_Output' tab; this information feeds the entire model. Lookup arrays and commonly sourced definitions (e.g. unit conversions, densities) reside in the 'Development' tab and should not be modified unless by a user aiming to significantly modify the model. Table 3-1 describes the separate tabs that exist for organizing transportation, water, electricity, fuel pre-combustion, and fuel combustion related data. Other common data tabs house information on facility energy use, TRACI characterization factors, and the model's references.



The user input for the structural material pathways feeds the lumber, steel, and concrete modules. These modules are comprised of tabs which represent major processes and life cycle phases. These modules, phases, and the user inputs that define them are listed in Table 3-2, Table 3-4, and Table 3-6.

Users can identify the phases associated with these modules in the B-PATH model based on the tab's color. Similar to the diagrams on the following pages, the modules in the spreadsheet follow this convention: Wood-Green, Concrete-Orange, Steel-Purple.

Inventories of water, electricity, fuel, and materials are organized for each phase in each module. Emissions factors from the common data tabs are multiplied by the phase inventories to calculate the total phase impacts. These emission inventories are summed and collected on the 'Cement Results,' 'Wood Results,' and 'Steel Results' tabs.

The user also has control over assumptions related to the building's size, location, construction, use, and the materials' end-of-life pathways. Descriptions of these modules and the user inputs that define them can be found in Tables 3-7 to 3-9.

The inventories and related emissions from these phases are added to the structural material results and compiled in the 'Summary' tab. Emission inventories are multiplied by TRACI characterization factors to calculate an LCI assessment for the building.

The tables below are meant as reference sheets for individual worksheets in the B-PATH model. For ease of access to information relevant to specific processes, materials, and phases, the worksheet inputs and functions are described in a concise tabular fashion (rather than in a narrative fashion) in the remainder of this chapter.

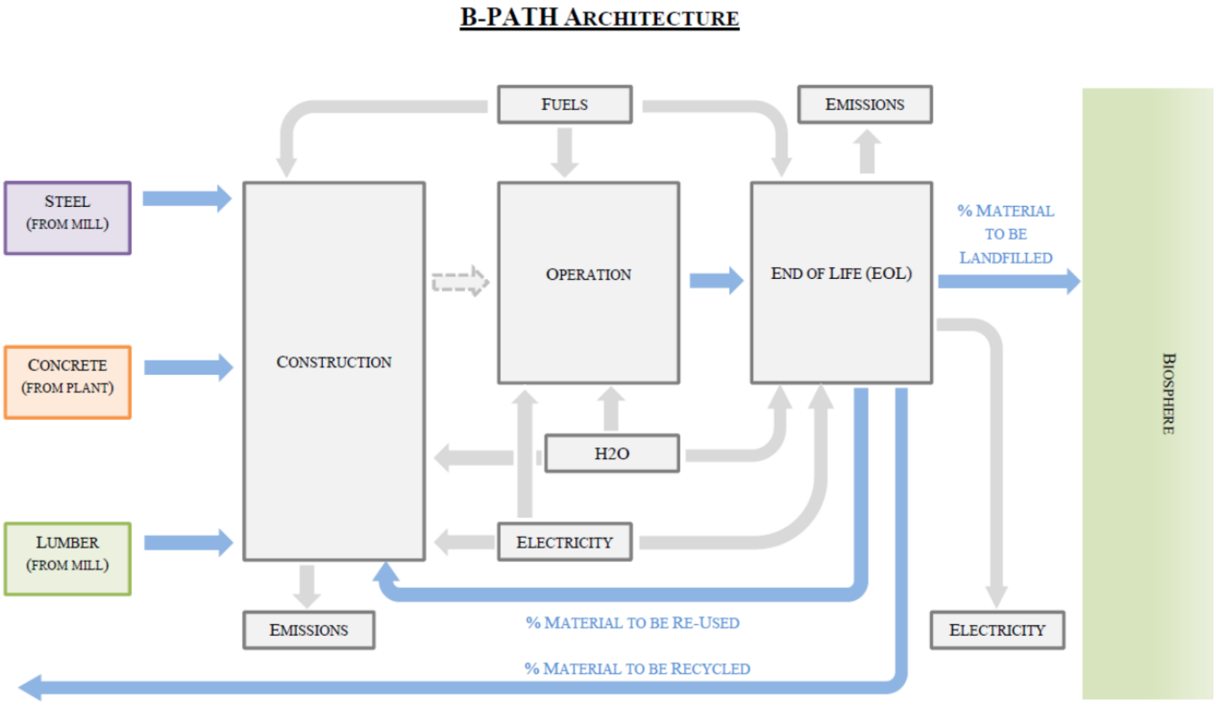


Figure 3-1. Schematic of B-PATH architecture

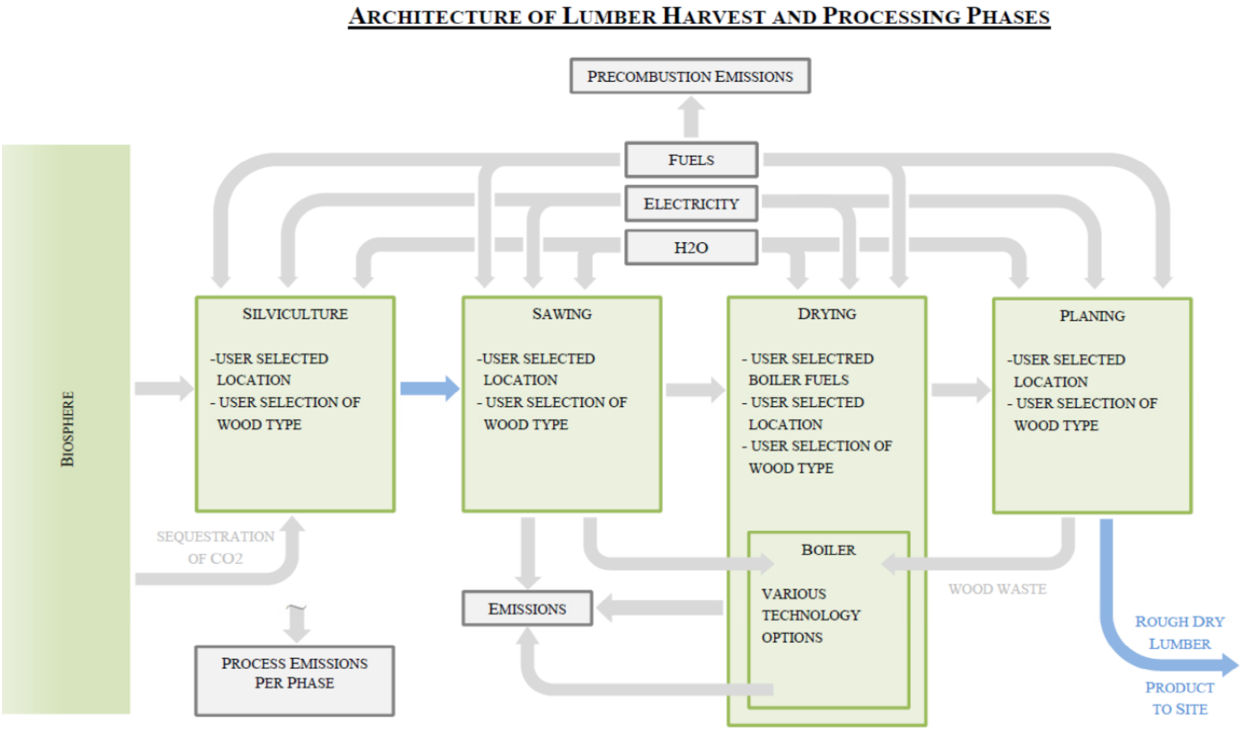


Figure 3-2. Schematic of B-PATH lumber module

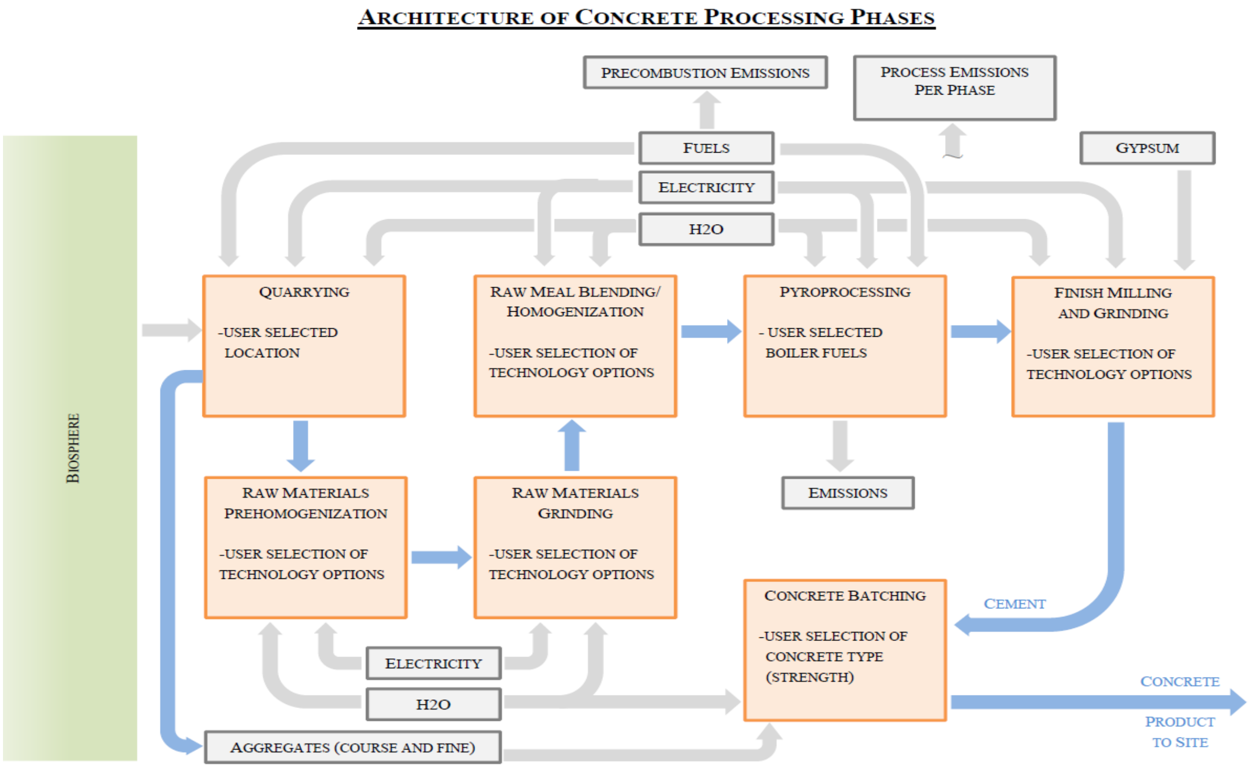


Figure 3-3. Schematic of B-PATH concrete module

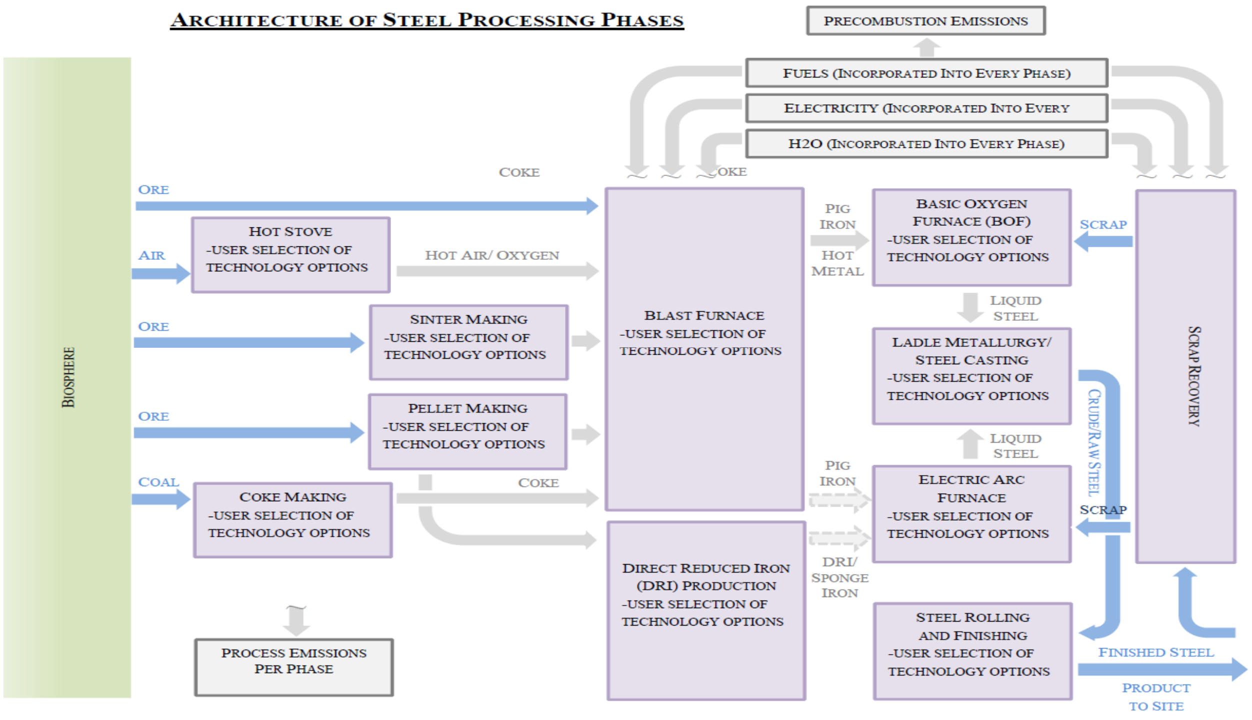


Figure 3-4. Schematic of B-PATH steel module

Table 3-1. Model Architecture- Common Data Tabs

Common Data Tabs	
Organized data used to calculate LCIs	
Related Tabs	
Development	Contains lookup tables for unit conversions, major products, included phases, product densities, states, regions, etc.
Transport	Contains inventory data for the combustion of transport fuels for 10 common modes and calculates the emissions related to each transport phase in the LCA model.
	User Inputs (from Input_Output Tab) which Affect this Module:
	Transportation of Logs to Storage (Distance and Conveyance Mode)
	Transportation of Logs to Sawmill (Distance and Conveyance Mode)
	Transportation of Product of Each Phase Within the Cement Plant (and Conveyance Mode)
	Transportation of Raw Materials to Cement Plant (Distance and Transportation Mode)
	Transportation of Raw Materials to Steel Plant (Distance and Transportation Mode)
	Transportation of Planed Dry Lumber to Construction Site (Distance and Conveyance Mode)
	Transportation of Concrete to Construction Site (Distance and Conveyance Mode)
	Transportation of Steel to Construction Site (Distance and Conveyance Mode)
	End-of-Life Transportation of Lumber (Distance and Conveyance Mode)
	End-of-Life Transportation of Steel (Distance and Conveyance Mode)
	End-of-Life Transportation of Concrete (Distance and Conveyance Mode)
Pre Fuel Data	Organizes lookup tables of the primary energy to extract and process fuels prior to combustion.
Combust_Fuel_Data	Estimates the combustion emissions of selected common fuels.
Grid Data	Contains lookup tables for the grid mixes and related emissions from the US States and estimates emissions caused by the 6 customizable user-defined grids. These calculations also add the pre-combustion emissions of the processed fuels.
	User Inputs (from Input_Output Tab) which Affect this Module:
	Definition of up to six (6) Custom Electricity Grids
Water	Contains data on industrial self-supplied and public-supply water withdrawals per state and calculates emissions related to water use per each phase.
Facilities	Estimates the electricity, diesel fuel, and natural gas use in sawmills, steel mills, and cement plants for non-process uses. This tab estimates facility-related indirect emissions for each material.
	User Inputs (from Input_Output Tab) which Affect this Module:
	Size of Sawmill (ft^2)
	Size of Cement Plant (ft^2)
	Size of Steel Mill (ft^2)
	Mass or Volume of Planed Dry Lumber Used in Building (Variable Unit Type)
	Mass or Volume of Concrete Used in Building (Variable Unit Type)
	Mass or Volume of Steel Used in Building (Variable Unit Type)
Balance	Contains LCI data on "balance of building" materials and elements
TRACI	Contains the TRACI impact category weighting factors for the calculation of a life cycle assessment for the defined function unit.

Table 3-2. Model Architecture- Lumber Production Module

Lumber Module	
LCI for the production of user specified mass or volume of planed dry lumber	
Related Tabs	
W_Silviculture	Estimates kg CO2e emitted and sequestered during tree growth given user input data related to silviculture decisions.
W_Sawing	Inventories materials, energy, etc. that characterize the sawing of logs into rough green lumber. Calculations are performed by conducting a material flow analysis based on common practices in the sawmill region.
W_Boilers	Organizes data from 23 common boiler types used to combust fuel during the kiln drying stage. Calculations are performed to estimate emissions given user selected fuels, boilers, and emission control technologies.
W_Kiln Drying	Inventories materials, energy, etc. that characterize the kiln drying of rough green lumber to rough dry lumber. Calculations are performed by conducting a material flow analysis based on common practices in the sawmill region.
W_Planing	Inventories materials, energy, etc. that characterize the planing of rough dry lumber to planed dry lumber. Calculations are performed by conducting a material flow analysis based on common practices in the sawmill region.
Calculated Inventory:	
	Electricity Consumption (kWh)
	Fuel Consumption (Units Vary)
	Water Consumption (m3)
	Total Solid Waste Generation (kg)
	Air Emissions (111 Emissions Tracked)
	Water Emissions (90 Emissions Tracked)

Table 3-3. Summary of User Inputs for Lumber Production Module

Lumber Module User Inputs (Located in the 'Input_Output' Tab)					
User Inputs:	W_Silviculture	W_Sawing	W_Boilers	W_Kiln Drying	W_Planing
Mass or Volume of Planed Dry Lumber Used in Building (Variable Unit Type)	X	X	X	X	X
US State or Custom Electricity Grid for Location of Forest	X				
Source of Water at Forest	X				
Forest Rotation Age (Years)	X				
Forest Initial Planting Density	X				
Forest Site Preparation Options	X				
US State or Custom Electricity Grid for Location of Sawmill (Model Defines a Region)		X	X	X	X
Type of Wood (Model Suggests Based on Region)	X	X	X	X	X
Source of Water at Sawmill (Public or Industrial)		X	X	X	X
Fuel Inputs to Kiln Drying as % of Total Drying Energy			X	X	
Selection of Boiler Type for each Kiln Fuel			X	X	
Selection of Emission Control Technology for each Boiler Type			X	X	

Table 3-4. Model Architecture- Concrete Production Module

Concrete Module	
LCI for the production of user specified mass or volume of concrete	
Related Tabs	
C_Raw Meal	Inventories materials (both quarried materials and industrial by-products), fuels, electricity and water inputs as well as associated air, water and solid emissions related to quarrying, raw materials prehomogenization, raw materials grinding, and raw meal blending/homogenization processes given user input data related to relevant technology options. Calculations are performed to estimate emissions from electricity use (for all processes), fuel pre-combustion related (only for quarrying), fuel combustion related (only for quarrying) and process related (for all four processes in this tab).
C_Pyroprocess	Organizes and inventories materials, fuels, electricity and water input and associated output data from four common types of U.S. cement kilns. Calculations are performed to estimate emissions for preparation of 7 traditional and 10 waste fuels preparation and pyroprocessing for 4 kiln technology options and 1 US average kiln option. LCI data is performed for electricity use (for both fuels preparation and pyroprocessing), fuel pre-combustion related (only for fuels preparation), fuel combustion related (only for pyroprocessing), and process related (for pyroprocessing and fuels preparation)
C_Clinker Cooling	Inventories electricity and water inputs and associated emissions from clinker cooling stage. Calculations are performed to estimate emissions from electricity use and process-related given user input data for 6 cooling technology options and 2 emission control options.
C_Finish	
Mill Grind	Inventories material (gypsum and clinker mix), electricity and water inputs and associated emissions from cement finish milling and grinding. Calculations are performed to estimate emissions from electricity use and process-related given user input data for 5 grinding and milling technology options.
C_SCM	The Additives and Supplementary Cementitious Preparation and Mixing with PC tab organizes data for material inputs of industrial by-products (fly ash, granulated blast furnace slag) and additives (gypsum, limestone, CKD) that are either added to clinker or cement by separate grinding or dry mixing. Calculations are performed to estimate electricity and water use requirement and associated emissions for grinding of clinker with gypsum (for traditional Portland cement Type I-V), separate grinding of limestone and industrial by-products (fly ash, granulated blast furnace slag, etc.) for (blended cements and cement with CKD) and dry mixing with Portland cement.
C_Aggregates	Organizes and inventories material (sand, gravel, and rock), electricity, fuel and water inputs and associated emissions from fine and coarse aggregates at the quarry.
C_Admixtures	Organizes and inventories electricity and fuel inputs and associated emissions for six major types of admixtures (plasticiser, superplasticiser, retarder, accelerating admixture, air entraining admixture, and waterproofing type.
Calculated Inventory:	
	Electricity Consumption (kWh)
	Fuel Consumption (Units Vary)
	Water Consumption (m^3)
	Total Solid Waste Generation (kg)
	Air Emissions (111 Emissions Tracked)
	Water Emissions (90 Emissions Tracked)

Table 3-5. Summary of User Inputs for Concrete Production Module

Concrete Module User Inputs (Located in the 'Input_Output' Tab)							
User Inputs:	C_Raw Meal	C_Pyroprocess	C_Clinker Cooling	C_Finish Mill Grind	C_SCM	C_Aggregates	C_Admixtures
Concrete Product Type (Low Strength, Moderate Strength, High Strength)	X	X	X	X	X	X	X
Mass or Volume of Concrete, Admixtures, Aggregates, Cement, and Water Used in Building (Variable Unit Type)	X	X	X	X	X	X	X
Admixture Type (Plasticiser, Superplasticiser, Retarder, Accelerating, Air entraining, Waterproofing)							X
US State or Custom Electricity Grid for Location of Quarry	X						
Source of Water at Quarry	X						
US State or Custom Electricity Grid for Location of Aggregate Quarrying						X	
Source of Water at Aggregate Quarrying						X	
US State or Custom Electricity Grid for Location of Admixture Production							X
Source of Water at Admixture Production							X
US State or Custom Electricity Grid for Location of Cement Plant		X	X	X	X		
Source of Water at Cement Plant		X	X	X	X		
Selection of Raw Materials Prehomogenization Technology	X						
Selection of Raw Materials Grinding Technology	X						
Selection of Raw Meal Blending/Homogenization Technology	X						
Selection of Pyroprocessing		X					
Selection of Clinker Cooling Technology			X				
Selection of Dust Emission Control Technology for Cooling			X				
Selection of Finish Milling and Grinding Technology				X			
Selection of Supplementary Cementitious Material Type for Calculating Impacts from Preparation and Mixing with Cement					X		
Fuel Inputs to Clinker Pyroprocessing as % of Total Energy Based on Traditional or Alternative Fuel Inputs		X					

Table 3-6. Model Architecture- Steel Production Module

Steel Module	
LCI for the production of user specified mass or volume of steel	
Related Tabs	
S_Mining	Inventories fuel and water inputs for extraction equipment operations, materials handling equipment (e.g., conveyors), and beneficiation and processing operations for raw materials extraction.
S_Sinter	Inventories fuel, water, and materials inputs for conversion of ore to sinter, for subsequent use in blast furnaces. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
S_Pellet	Inventories fuel, water, and materials inputs for conversion of ore to pellets, for subsequent use in blast furnaces. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
S_Coking	Inventories fuel, water, and materials inputs for conversion of coal feedstock to coke and coke oven gas, for subsequent use in blast furnaces and other processes. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
S_Blast_Furnace	Inventories fuel, water, and materials inputs for processing of sinter, pellets, scrap, coke, and other inputs to produce molten pig iron and blast furnace gas. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
S_BOF	Inventories fuel, water, and materials inputs for processing of molten pig iron into liquid steel. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
S_DRI	Inventories fuel, water, and materials inputs for processing of ore into sponge iron. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data. DRI production is not common in the United States, but is included for comprehensiveness and for assessing possible import scenarios.
S_Scrap	Inventories fuel requirements for recovery and processing of steel scrap for subsequent use in blast furnaces and EAFs.
S_DRI_EAF	Inventories fuel, water, and materials inputs for processing of sponge iron into liquid steel. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data. DRI EAF production is not common in the United States, but is included for comprehensiveness and for assessing possible import scenarios.
S_R_EAF	Inventories fuel, water, and materials (e.g., carbon) inputs for processing of steel scrap into liquid steel. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
S_Liquid_	
Mix	Allows for specification of mix of liquid steel based on percent from blast furnace-BOF route, DRI-EAF route, and scrap-EAF route to assess different ratios of virgin to recycled steel, and different technologies for producing virgin and recycled steel. User has the option of using the “closed loop” approach as endorsed by several metals association to account for circularities in the production system for steel. Calculates the LCI of the user specified mix based on mass quantities of outputs from each process tab necessary for a ton of finished, hot rolled structural or reinforcement steel.
S_Casting	Inventories fuel, water, and materials inputs for continuous (common) and ladle

	(uncommon) casting of liquid steel. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
S_Reheat	Inventories fuel and materials inputs for reheat furnaces in rolling mills.
S_Forming	Inventories fuel, water, and materials inputs for hot rolling to produce structural and reinforcement bar shapes. Calculations are based on energy and mass balance data, and non-energy related process emissions and water use data.
Calculated Inventory:	
	Electricity Consumption (kWh)
	Fuel Consumption (Units Vary)
	Water Consumption (m^3)
	Air Emissions (111 Emissions Tracked)
	Water Emissions (90 Emissions Tracked)

Table 3-7. Model Architecture- Construction Module

Construction Module	
LCI for the construction of the building structural frame	
Related Tabs	
Construction:	Module calculates energy and water usage based on construction equipment characteristics (model, model year, cum mileage, carrying capacity, etc. of non-road and road heavy diesel vehicles as well as other small equipment) use hours and energy sources (electricity, diesel, gasoline) and transportation of building materials and equipment to and from site (using material and equipment weights, distances and transportation mode).
	User Inputs (from Input_Output Tab) which Affect this Module:
	Building's Primary Structural Material
	US State or Custom Electricity Grid
	Building Representative City, State (16 Climate Zone Options)
	Building's Area (ft^2)
	Source of Water (Public or Industrial)
	Number of Equipment Use Hours (Hours)
	Construction Equipment Model and Year Properties
	Bill of Major Materials (in tonnes or $US)
	Transportation Distance for Equipment and Materials (km)
	Heavy Duty Diesel Truck Year, Model, Capacity, mpg Properties
Calculated Inventory:	
	Electricity Consumption (kWh)
	Natural Gas Consumption (m^3)
	Water Consumption (m^3)
	Total Solid Waste Generation (kg)
	Air Emissions (111 Emissions Tracked)
	Water Emissions (90 Emissions Tracked)

Table 3-8. Model Architecture - Operation Module

Operation Module	
LCI for the operation of building during its use phase	
Related Tabs in PCA Model:	
Operation:	Module provides estimates of electricity, natural gas, and water usage over the specified lifespan of the building given its area and location.
	User Inputs (from Input_Output Tab) which Affect this Module:
	Building's Primary Structural Material
	US State or Custom Electricity Grid
	Building Representative City, State (16 Climate Zone Options)
	Building's Area (ft^2)
	Building's Assumed Lifespan (Years)
	Source of Water (Public or Industrial)
Calculated Inventory:	
	Electricity Consumption (kWh)
	Natural Gas Consumption (m^3)
	Water Consumption (m^3)
	Total Solid Waste Generation (kg)
	Air Emissions (111 Emissions Tracked)
	Water Emissions (90 Emissions Tracked)

Table 3-9. Model Architecture - End of Life Module

End of Life Module	
LCI for the disposal and end-of-life pathways after demolishing building	
Related Tabs in PCA Model:	
EOL:	Module summarizes the impacts of the end-of-life fate of lumber, steel, and concrete
	User Inputs (from Input_Output Tab) which Affect this Module:
	Transportation Distances to Recycling Center, Landfill
	Waste Estimates for Major Building Materials
	Demolishing Equipment Model and Year Properties
	Heavy Duty Diesel Truck Year, Model, Capacity, mpg Properties
Calculated Inventory:	
	Electricity Consumption (kWh)
	Natural Gas Consumption (m^3)
	Water Consumption (m^3)
	Total Solid Waste Generation (kg)
	Air Emissions (111 Emissions Tracked)
	Water Emissions (90 Emissions Tracked)

Table 3-10. Model Architecture - Results

Results Tabs	
These tabs summarize the results of the LCI and LCIA	
Related Tabs in PCA Model:	
Concrete Results	This tab organizes the LCI results of all phases related to concrete structures
Wood Results	This tab organizes the LCI results of all phases related to lumber structures
Steel Results	This tab organizes the LCI results of all phases related to steel structures
Building Results	This tab organizes the LCI results of all phases related to construction, operation, and end of life of the building.
Summary	This tab summarizes the LCIA results

4. CASE STUDY

This chapter summarizes the results of a case study application of B-PATH. The case study considers a prototype low-rise commercial building in California. A California case study was chosen based on availability of credible data for alternate structural materials designs, the diversity of climate zones within the state, and the unique supply chain characteristics associated with the state's cement production pathways. The case study was meant to highlight B-PATH's capabilities in modeling regional and technology variations, and for exploring how different structural materials pathway scenarios might affect the life-cycle results for the case study building.

The data presented below comprise the key case study inputs into B-PATH, and a concise summary of results. For details on assumptions related to process LCIs, emission factors, data sources, etc., the reader is referred to the B-PATH model file.

4.1. Case Study Scope

The case study considers a prototype low-rise commercial building, for which structural, envelope, and balance of building data have been previously derived based on architectural designs for two equivalent structures: (1) a reinforced concrete frame, and (2) a steel frame (Guggemos 2003). The case study was focused on assessment of life-cycle greenhouse gas (GHG) emissions associated with these two structural materials options, given the particular relevance of GHG emissions in policy and planning decisions in California in light of the state's long-term GHG reduction targets. (Under the Global Warming Solutions Act of 2006, California has committed to reducing its greenhouse gas (GHG) emissions to 80% below 1990 levels by the year 2050.)

In particular, the case study explored how different material pathways might influence the life-cycle GHG emissions associated with the prototype building in different California climate zones. Furthermore, the case study was designed to consider plausible variations in materials pathway technologies that can be modeled using B-PATH. For example, **Error! eference source not found.** through Figure 4-4 summarize B-PATH estimates for different technology scenarios associated with the cradle-to-gate systems for hot-rolled steel (blast furnace – BOF route[1]) and cement. The influence of such technology variations on the life-cycle GHG emissions of the prototype building was considered for the reinforced concrete and steel frame designs.

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[1] In the case study, steel produced from the scrap-EAF route was also included in the liquid steel mix; see assumptions below.

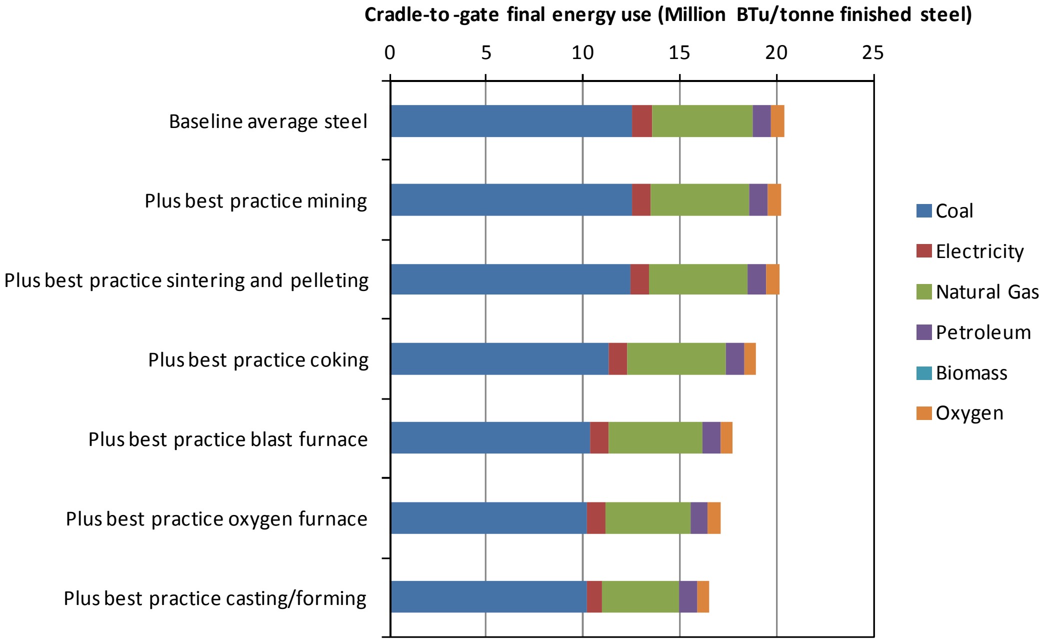


Figure 4-1. Estimated cradle-to-gate final energy use of steel under different technology scenarios (blast furnace-BOF route)

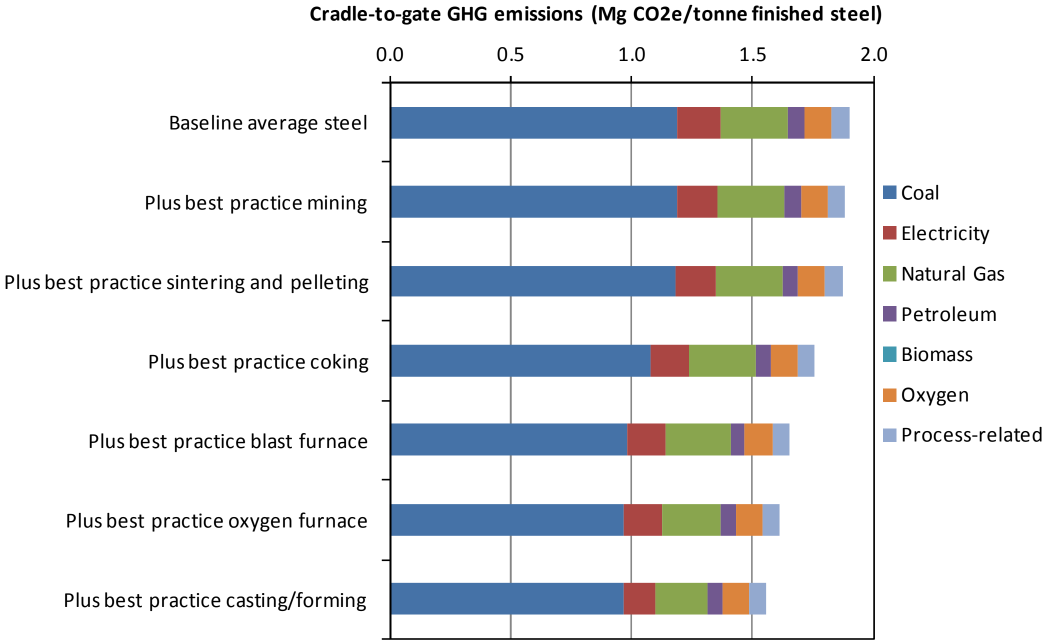


Figure 4-2. Estimated cradle-to-gate GHG emissions of steel under different technology scenarios (blast furnace-BOF route)

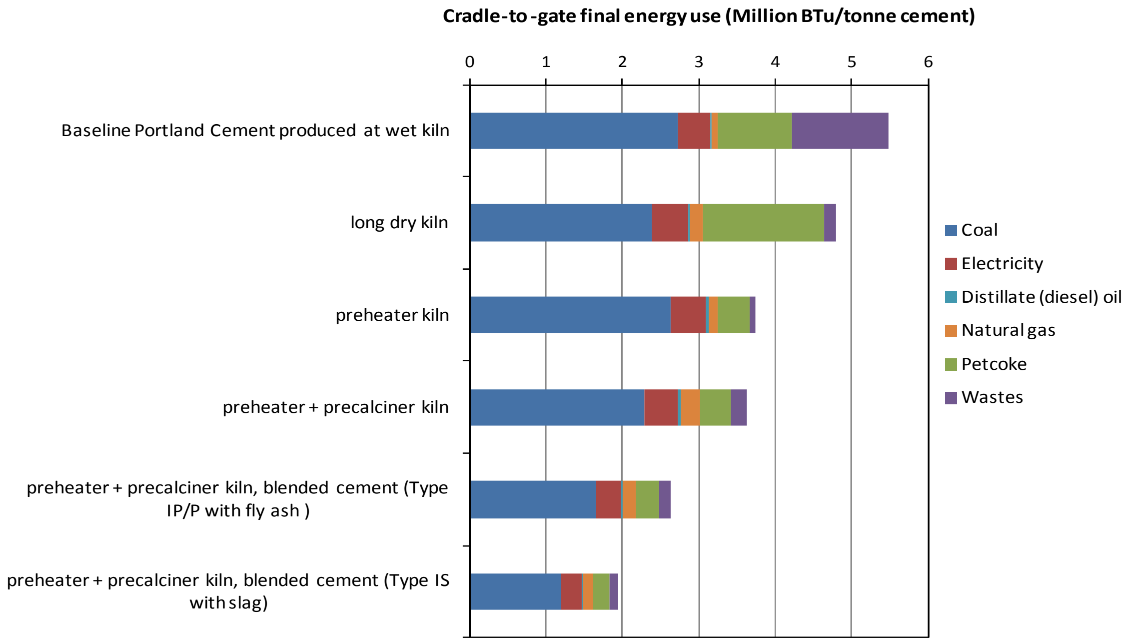


Figure 4-3. Estimated cradle-to-gate final energy use of cement under different technology scenarios

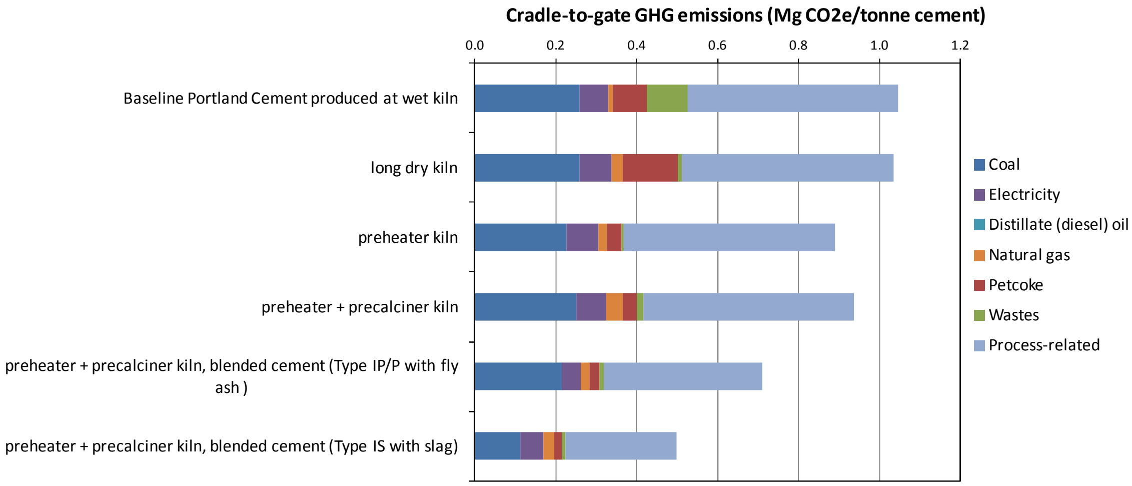


Figure 4-4. Estimated cradle-to-gate GHG emissions of cement under different technology scenarios

4.2. Prototype Building Characteristics

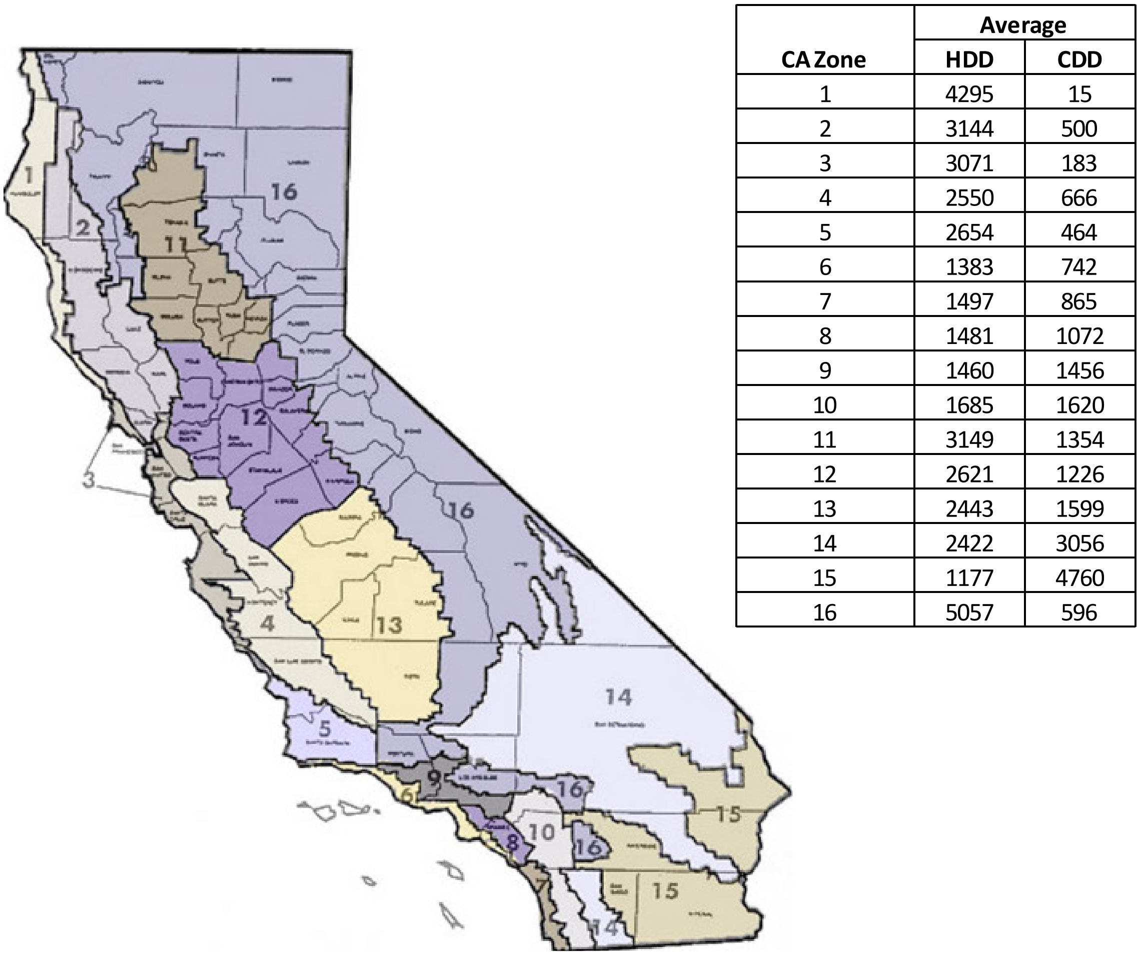
The low-rise prototype commercial building was assumed to be a three-story structure with 47,000 square feet of internal floor area (4,366 square meters) and an economic lifespan of 50 years, based on data in Guggemos (2003). The assumed quantities of structural and balance of building materials and elements are summarized in **Error! Reference source not found.**. The rototype building materials estimates assume compliance for California building energy codes for new construction (Title 24, 2005 standards).

Table 4-1. Case Study Material Quantities

Total kg		
Bill of materials	Steel frame	Concrete frame
Structural		
Steel (structural)	4.0E+05	0.0E+00
Steel (rebar)	6.2E+04	2.7E+05
Concrete	1.1E+06	3.0E+06
Balance of building		
Aluminum	1.7E+03	1.7E+03
Bitumen	1.1E+04	1.1E+04
Carpet	1.2E+04	1.2E+04
Ceramic tile	2.1E+04	2.1E+04
Elevator	2.8E+03	2.8E+03
Mineral fiber board ceiling tile	1.1E+04	1.1E+04
Fire Retardant	1.1E+03	0.0E+00
Glass	1.2E+05	1.2E+05
Gypsum board	1.3E+05	1.3E+05
Insulation - Extrud. Polystyrene	1.7E+03	1.7E+03
Insulation - Fiberglass	5.3E+03	5.3E+03
Paint	1.1E+03	1.1E+03
Steel - Metal stairs	1.6E+04	1.6E+04
Steel - studs, doors, frames, grid	3.0E+04	3.0E+04
Water heater	8.2E+02	8.2E+02
HVAC multizone units	1.8E+04	1.8E+04
Switchgear	5.0E+02	5.0E+02
Emergency generator	5.0E+02	5.0E+02
Copper - tubing and wire	6.0E+02	6.0E+02
Steel - piping, ductwork	3.8E+04	3.8E+04
Polypropelene - piping	2.0E+00	2.0E+00

4.3. Operational Energy Use

Figure 4-5 depicts the sixteen California building climate zones, as defined by the California Energy Commission (CEC 2010), with average heating degree days (HDD) and cooling degree days (CDD) values per climate zone derived from (PEC 2006). As seen in the figure, the average HDD and CDD vary significantly across the state, the geography of which includes mountain, desert, and coastal regions.



CA Zone	Average	
	HDD	CDD
1	4295	15
2	3144	500
3	3071	183
4	2550	666
5	2654	464
6	1383	742
7	1497	865
8	1481	1072
9	1460	1456
10	1685	1620
11	3149	1354
12	2621	1226
13	2443	1599
14	2422	3056
15	1177	4760
16	5057	596

Figure 4-5. Map of California climate zones with average HDD and CDD by zone

Table 4-2 and Table 4-3 summarize the estimated annual operational energy use for the prototype building by climate zone and major building system for the concrete and steel frame designs, respectively. These values were estimated based on California energy end use model for commercial buildings by climate zone (Itron and KEMA 2008) with thermal mass effect adjustments for the concrete framed structure as follows: climate zones 1,16 (heating loads reduced by 6% compared to steel frame); climate zones 2-13 (heating loads reduced by 7%); climate zones 14, 15 (heating loads reduced by 7%). The thermal mass adjustments were made based on a review of EnergyPlus modeling data for similar structures in equivalent climate zones, and are consistent with values published in previous studies (Marceau and VanGeem 2007b). However, these estimates should be refined and/or validated in future research through dedicated whole-building energy simulations for each frame type and climate zone, which were beyond this project’s scope and resources.

Table 4-2. Estimated Annual Operating Energy Use for the Prototype Building (Concrete Frame)

New Construction: Annual Electricity Use Energy Intensity (kWh/square foot)																
End Use/Climate Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Heating	0.0	0.0	0.4	0.4	0.4	0.2	0.4	0.2	0.2	0.4	0.2	0.1	0.2	0.2	0.0	0.1
Cooling	0.7	0.7	2.7	3.4	2.0	3.1	3.1	3.1	2.8	3.1	2.6	2.1	2.6	2.8	2.4	1.7
Ventilation	0.7	0.7	2.7	3.5	2.0	2.1	2.4	2.1	2.5	2.4	1.0	1.1	1.0	1.5	0.5	1.8
Water Heating	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.2	0.3	0.1
Cooking	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.0	0.1
Refrigeration	0.1	0.1	0.3	0.4	0.2	0.3	0.6	0.3	0.4	0.6	0.3	0.2	0.3	0.4	0.2	0.3
Exterior Lighting	0.4	0.4	0.3	0.5	0.2	0.5	0.5	0.5	0.6	0.5	0.6	0.5	0.6	0.4	0.4	0.5
Interior Lighting	3.4	3.4	3.5	3.5	3.4	4.0	3.6	4.0	3.6	3.6	3.2	3.1	3.2	3.7	3.9	3.3
Office Equipment	0.6	0.6	3.8	5.1	2.5	3.0	2.4	3.0	2.7	2.4	1.8	1.5	1.8	1.9	1.4	1.5
Miscellaneous	0.1	0.1	0.5	0.7	0.3	0.5	0.8	0.5	0.4	0.8	0.7	1.0	0.7	0.5	0.2	0.2
Process	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Motors	0.8	0.8	0.5	0.4	0.7	0.5	0.8	0.5	0.5	0.8	0.5	0.5	0.5	0.5	0.3	0.7
Air Compressors	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1
Total	7.2	7.1	15.0	18.1	11.8	14.5	14.8	14.5	13.9	14.8	11.0	10.4	11.0	12.3	9.6	10.4

New Construction: Annual Natural Gas Use Energy Intensity (kBtu/square foot)																
End Use/Climate Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Heating	17.6	17.1	17.7	18.5	16.8	8.2	20.9	8.2	8.5	20.9	16.4	12.6	16.4	12.1	3.1	13.3
Cooling	0.0	0.0	0.0	0.0	0.0	0.5	2.2	0.5	0.4	2.2	0.0	0.0	0.0	1.1	0.0	0.2
Water Heating	1.1	1.1	2.5	3.5	1.6	2.3	3.8	2.3	1.6	3.8	6.2	4.4	6.2	1.9	0.1	1.0
Cooking	0.0	0.0	0.1	0.1	0.1	0.4	0.2	0.4	0.3	0.2	0.7	0.4	0.7	0.1	0.0	0.1
Miscellaneous	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0
Process	0.0	0.0	0.5	0.0	1.0	0.0	5.7	0.0	0.0	5.7	0.0	0.0	0.0	2.8	0.0	0.0
Total	18.7	18.2	20.8	22.1	19.4	11.7	32.9	11.7	11.0	32.9	23.4	17.3	23.4	18.2	3.2	14.6

Table 4-3. Estimated Annual Operating Energy Use for the Prototype Building (Steel Frame)

New Construction: Annual Electricity Use Energy Intensity (kWh/square foot)																
End Use/Climate Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Heating	0.0	0.0	0.5	0.5	0.4	0.2	0.4	0.2	0.2	0.4	0.2	0.1	0.2	0.2	0.0	0.1
Cooling	0.7	0.7	2.9	3.7	2.1	3.4	3.4	3.4	3.1	3.4	2.8	2.3	2.8	3.0	2.6	1.8
Ventilation	0.7	0.7	3.0	3.8	2.1	2.3	2.6	2.3	2.7	2.6	1.1	1.2	1.1	1.6	0.6	1.9
Water Heating	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.2	0.3	0.1
Cooking	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.0	0.1
Refrigeration	0.1	0.1	0.3	0.4	0.2	0.3	0.6	0.3	0.4	0.6	0.3	0.2	0.3	0.4	0.2	0.3
Exterior Lighting	0.4	0.4	0.3	0.5	0.2	0.5	0.5	0.5	0.6	0.5	0.6	0.5	0.6	0.4	0.4	0.5
Interior Lighting	3.4	3.4	3.5	3.5	3.4	4.0	3.6	4.0	3.6	3.6	3.2	3.1	3.2	3.7	3.9	3.3
Office Equipment	0.6	0.6	3.8	5.1	2.5	3.0	2.4	3.0	2.7	2.4	1.8	1.5	1.8	1.9	1.4	1.5
Miscellaneous	0.1	0.1	0.5	0.7	0.3	0.5	0.8	0.5	0.4	0.8	0.7	1.0	0.7	0.5	0.2	0.2
Process	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Motors	0.8	0.8	0.5	0.4	0.7	0.5	0.8	0.5	0.5	0.8	0.5	0.5	0.5	0.5	0.3	0.7
Air Compressors	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1
Total	7.2	7.2	15.5	18.8	12.2	15.0	15.4	15.0	14.4	15.4	11.4	10.7	11.4	12.6	9.8	10.6

New Construction: Annual Natural Gas Use Energy Intensity (kBtu/square foot)																
End Use/Climate Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Heating	18.7	18.7	19.3	20.2	18.3	8.9	22.8	8.9	9.3	22.8	17.9	13.7	17.9	13.0	3.3	14.2
Cooling	0.0	0.0	0.0	0.0	0.0	0.6	2.4	0.6	0.5	2.4	0.0	0.0	0.0	1.2	0.0	0.2
Water Heating	1.1	1.1	2.5	3.5	1.6	2.3	3.8	2.3	1.6	3.8	6.2	4.4	6.2	1.9	0.1	1.0
Cooking	0.0	0.0	0.1	0.1	0.1	0.4	0.2	0.4	0.3	0.2	0.7	0.4	0.7	0.1	0.0	0.1
Miscellaneous	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0
Process	0.0	0.0	0.5	0.0	1.0	0.0	5.7	0.0	0.0	5.7	0.0	0.0	0.0	2.8	0.0	0.0
Total	19.8	19.8	22.4	23.7	21.0	12.5	35.0	12.5	11.8	35.0	24.8	18.5	24.8	19.2	3.4	15.5

4.4. Materials Pathway Scenarios

Table 4-4-4 summarizes the materials pathway technology scenarios that were considered in the case study. Given that both steel and concrete are necessary materials in both structural frame options, the technology options for each material pathway were assigned to both structure types in each scenario.

Table 4-4. Summary of Pathway Scenarios Considered for the Prototype Building

Scenario	Name	Description	Values (kg CO2e/kg)
A	Baseline	This scenario assumes best available, average cradle-to-gate GHG emissions data from the literature for steel and concrete. These values are taken from Ochsendorf et al. (2011). The liquid steel mix (expressed as % blast furnace-BOF steel : % scrap-EAF steel) is 40:60 for structural steel and 30:70 for rebar.	Cement: 0.93 Steel: 1.00 (structural) Steel: 1.24 (rebar)
B	Imported cement, best practice steel (EAF)	This scenario assumes imported cement manufactured with a wet kiln in China, with values derived from B-PATH. Best practice steel (EAF route) is assumed from scenario.	Cement: 1.3 Steel: 0.67(structural) Steel: 0.67 (rebar)
C	Best practice concrete	This scenario assumes best practice concrete is used based on California production practices. The best practice values for concrete are derived from B-PATH. Baseline steel is assumed.	Cement: 0.85 Steel: 1.00 (structural) Steel: 1.24 (rebar)
D	Best practice concrete (blended cement)	This scenario assumes best practice concrete with IS cement based on California production practices from scenario (D). Best practice values concrete with IS cement are derived from B-PATH. Baseline steel is assumed.	Cement: 0.50 Steel: 1.00 (structural) Steel: 1.24 (rebar)
E	Best practice concrete and steel	Best practice EAF steel (scenario B) and best practice concrete with blended cement (scenario D)	Cement: 0.50 Steel: 0.67(structural) Steel: 0.67 (rebar)

4.5. Results

Figure 4-6 summarizes the results for the baseline scenario (A), expressed as the average results across all California climate zones by building life-cycle stage. Total life-cycle GHG emissions in the baseline scenario are estimated at 14,350 Mg CO2e for the steel framed building and 14,080 Mg CO2e for the concrete framed building. As seen in the figure, and consistent with past studies, the operational phase of the building life-cycle dominates the GHG emissions footprint, with raw materials production accounting for roughly 5% of the footprint. The lower estimated life-cycle emissions (on average for the state) associated with the concrete framed building are entirely attributable to lower life-cycle energy use due to the estimated thermal mass effects of concrete framed buildings. The general proportions of raw materials production, construction, operation, and end of life to the life-cycle GHG emissions footprint change little across all scenarios. However, the magnitude of the difference between the life-cycle GHG emissions footprints of steel and concrete framed buildings do vary across scenarios, and by climate zone, as summarized in Figure 4-7.

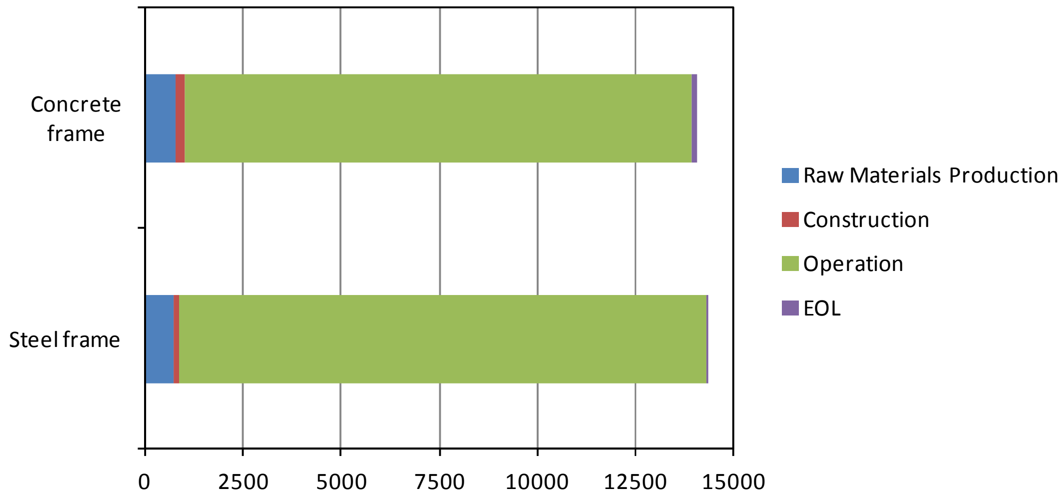


Figure 4-6. Results for the baseline scenario (average across climate zones)

The results in Figure 4-7 suggest three key trends for interpretation. First, for many climate zones the choice of scenario does not change the overall +/- sign of the difference; that is, either the steel framed or concrete framed building has a lower estimated life-cycle GHG emissions consistently across all five scenarios for a given climate zone. In such instances, the lowest estimated GHG emissions option is robust to different technology pathway assumptions. Furthermore, the use of baseline, average technology data from the literature would lead the analyst to identify the superior choice from a life-cycle GHG emissions perspective. Second, even for climate zones for which the results suggest a consistent superior choice there are appreciable differences between scenario results, which suggests that improved modeling of technological differences and materials pathway assumptions can result in significant differences in results at the regional level (i.e., when per-building results are multiplied by the building stock). Third, for some climate zones the superior option switched between scenarios, which suggests that the technology options might play a key role in determining which option has lower life-cycle GHG emissions in practice. For such instances, improved understanding and modeling of regional and technological variations in materials pathways is of particular importance for credible materials comparisons.

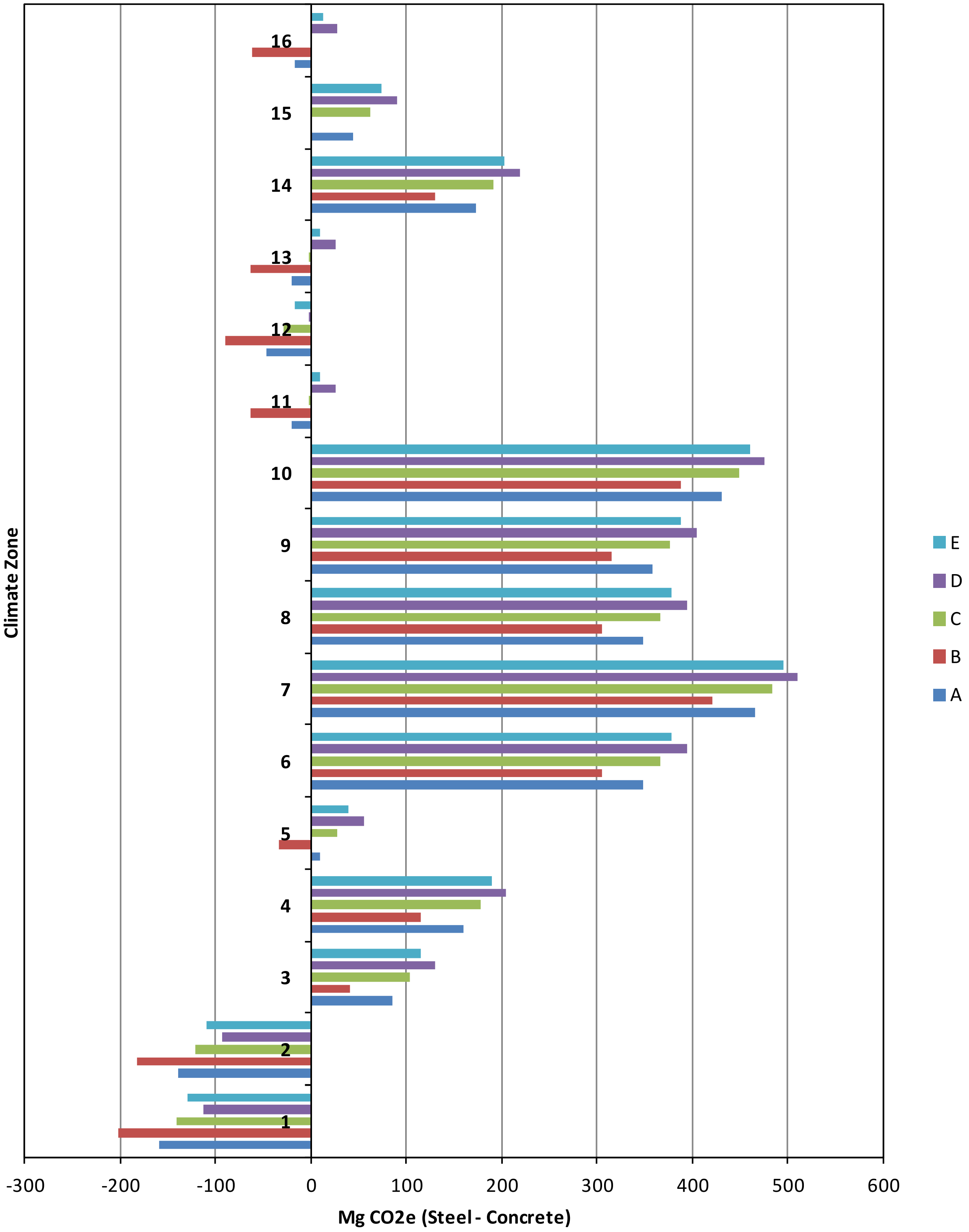


Figure 4-7. Differences between steel and concrete frames by climate zone and scenario

5. FUTURE WORK

Error! Reference source not found. provides recommendations for future research that will help improve the B-PATH model's capabilities and data. Furthermore, this future work should advance the general state of the art in building LCA, which should lead to more transparent, comprehensive, and credible building LCAs for use by building designers, planners, and environmental analysts.

The recommendations in **Error! Reference source not found.** are organized by research area for ease of access. No attempt has been made to prioritize or rank order the research recommendations in **Error! Reference source not found.** for the broader building LCA research community. The most important research gaps to address in any specific building LCA are highly dependent upon that study's available data, research questions, desired insights, and intended audience. Therefore, it is recommended that the research recommendations in **Error! Reference source not found.** be reviewed by LCA practitioners in the context of what is most important for his or her particular study.

Table 5-1. Recommendations for Future Research

Research Area	Specific Research Needs
System Boundary and Functional Unit	More robust modeling of the silviculture phase in wood production, including the effects of land management practices for inventorying fuel use, water use, etc. More robust modeling of mining, handling, and beneficiation practices for all raw materials for in the steel and concrete pathways, which currently rely on generic mining data, with particular attention to water use and wastewater generation. A better understanding of the impact of the assumptions for building lifespan, especially how this impacts maintenance and renovation activities. Comparison of structural materials options on a basis more relevant than mass or volume of material takeoffs for a specified lifespan. For example, more relevant functional unit elements could include structural carrying capacity, fire resistance, likelihood of structural damage due to natural events, and similar considerations made by the building design and planning communities. Improved understanding and modeling of the direct reuse potential for lumber, steel, and other building elements. Consideration of system boundary expansion to better model co-products generated in the building life cycle that might be consumed by other economic sectors, including wood waste in the lumber pathway, recycled aggregate in the concrete pathway, and exported electricity from self-generation in materials production.
Research Area	Specific Research Needs
Improved LCI data	More recent data sources and studies which collect regionally specific LCI data, including lumber, steel, and cement plant surveys and best practice technologies Sources which focus on engineered wood products (glulam, OSB, plywood) Development/improvement of understanding of the environmental impacts of chemical admixtures in concrete mixes through further research and market analysis Development of more sophisticated mass and energy balance models for steel production to better account for waste heat and process fuel (e.g., blast furnace and

	coke oven gas) generation and recovery across processes, and for different steel mill types Requirement for reliable and extensive data sources for understanding admixture production processes and related environmental inputs/outputs to/from these processes Improvement of cement kiln fuel combustion and precombustion emissions (PM, heavy metals, VOC, dioxins, furans) data (in addition to GHG emissions, NOx and SO2 emissions) for both alternative and traditional kiln fuels when data becomes available and transparent Improved data on economy-wide mass flows of virgin, reused, and recycled steel, concrete, and lumber to better account for production and end of life phase impacts of structural materials In-depth review of environmental impacts of the use of secondary materials in cement and concrete (SCMs, recycled concrete, alternative fuels), including an exhaustive list of potential materials Improvement of chemical admixtures LCI when U.S data becomes available Improved data on water consumption and wastewater generation, especially for alternative technology options More options for the allocation of wood co-products, other than use in wood boiler for kiln drying (e.g. sold to paper industry)

Research Area	Specific Research Needs
Regional and Technological Specificity	Better modeling of how capacity utilization can affect the specific energy and materials use (i.e., inputs per ton of outputs) of lumber, concrete, and steel production pathways Improved resolution in discrete technologies in steel making, to better model discrete aspects of best practice production methods Representation of best practice water and materials efficiency strategies and technologies for each structural material (B-PATH is currently limited to best practice energy efficiency) Inclusion of promising emerging technologies for assessment of future impact reduction potentials by materials pathway (e.g., carbon capture and sequestration at different plants, new materials such as geopolymer concretes) Improved modeling of combined heat and power options in materials production facilities, and the subsequent effects on plant level fuel demand and avoided central utilities
Use phase	Inclusion of whole-building energy simulation results for different structural and envelope materials configurations, to more accurately model operational energy consumption and its linkages to the types, mass, and forms of materials in the building. This could also include an evolving dataset of cases to be included in the B-PATH defaults for building materials and energy use data by climate zone. Better representation of maintenance activities and schedules for different building types
End-of-life Phase Considerations	Improved data regarding end-of-life statistics for structural building materials from the commercial sector (i.e., rates of landfilling versus recycling as well as national variations in end-of-life options) Improved understanding of recycling rates for concrete materials, including material

	flows and products using recycled concrete materials More options for the end-of-life fate of wood products, including the incorporation of better data on the reuse, recycling, and landfilling of wood products
LCIA	Inclusion of multiple LCIA indicator sets to assess modeling uncertainties between different LCIA methods Inclusion of county-level human health burdens from emissions across the building life cycle, to better characterize the external costs (and potential reductions) associated with different structural materials and building design options in different U.S. regions
General	Inclusion of available parameter uncertainty information to facilitate sensitivity analyses and results uncertainty analyses for a given modeling scenario Conduct additional case studies to further assess the robustness of the B-PATH model to different decision scenarios Compare results from B-PATH to those of commercial software tools, using a common case study, to understand differences and information asymmetries between public and commercial resources for building LCA

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APPENDIX A: LITERATURE REVIEWS

Prior to the development of the B-PATH architecture and modeling strategy, literature reviews were conducted for the three primary structural materials considered in this project (concrete, lumber, and steel). The goals of the literature review were to identify best available public sources for LCI data, to review the state of the art in modeling approaches for each material in order to build upon them, and to identify public data and modeling gaps that might be addressed by the B-PATH model. Internal literature review summaries were created for each structural material to guide B-PATH data and modeling decisions.

This appendix compiles these literature review summaries. Each was prepared by a different member of the research team, and thus the detail and emphases vary between summaries depending on the research findings. Additionally, because many data for steel production were available to the research team through past work at LBNL (Worrell et al. 2008, Worrell et al. 2010)—including a unit process best practice energy efficiency modeling framework (Worrell and Price 2006)—the literature review for steel was mainly focused on identifying additional LCI data sources. Thus, the summary for steel is limited to a concise inventory of data contained in different available public studies and datasets.

A.1. Cement and Concrete Literature Review

This section describes major Portland cement and concrete LCA studies conducted since late 1990s. Studies are selected from journal papers that follow systematic LCA guidelines, such as ISO 14040 framework for the purpose of enabling credible comparisons between studies. Additionally, major publicly available building material LCA tools are analyzed (e.g. BEES, ATHENA). Of the major Portland cement and concrete LCA studies reviewed, a few are complete LCAs with inclusion of both life-cycle inventory (LCI) and life-cycle impact assessment (LCIA) steps.

A glance at the Portland cement and concrete LCA literature (Table A-1) illustrates that major studies focus on certain environmental aspects (energy use and CO2 emissions) and specific constituents (Portland cement) of concrete. Literature does not provide stand-alone LCAs that cover environmental impacts of aggregates, admixtures, and supplementary cementitious materials. However, most concrete production LCA studies and tools (Lippiatt and Ahmad, 2004; Athena, 2005; Venta, 1999 ; Sjunnesson, 2005; Flower and Sanjayan, 2007; Lippiatt, 2007; Marceau et al., 2007; Collins, 2010) briefly evaluate impacts from the production of these raw materials in addition to Portland cement production. Almost all concrete raw material LCAs focus on the Portland cement production (Josa et al., 2004; Marceau et al., 2006; Josa et al., 2007; Boesch et al., 2009; Huntzinger and Eatmon, 2009; Boesch and Hellweg, 2010). However, Portland cement LCAs have their inherent shortcomings. Recent European Portland cement studies by (Josa et al., 2004; Josa et al., 2007) pinpoint to inaccurate and non-representative data with regards to the level of technology used and the geographical settings of cement production plants. For example, such data from technologically advanced plants or from countries with developed LCI database are not always representative of less advanced Portland cement plants or countries. Differing system boundaries and modeling assumptions further complicate environmental assessment of apparently a well-understood process of Portland cement production. As waste fuels and alternative raw materials are increasingly being used in Portland cement, the environmental assessment of Portland cement products gets more complicated. Moreover, data pertaining to other concrete ingredients (including admixtures, water, alternative fuels and materials) are limited and less available.

The literature review consists of two groups of studies: The first group covers Portland cement production LCA studies. The second group is a compilation of concrete and its raw materials production LCAs.

Table A-1. Environmental Life Cycle Inventory Categories Included in Reviewed Concrete LCA Studies and Tools.

	Raw materials extraction / production				*Concrete production*
LCI category	*Portland cement*	*Aggregates*	*Admixtures*	*SCMs*	
Raw materials	A,B,C,D,E,K,L,M,N,O,R	I,L,R	R	A,K	H,I,K,L,Y,P,R,U
Energy use	A,B,C,D,E,I,H,J,L,M,N,O,R,	F,H,I,L,R	F,R	A,K	G,H,I,K,L,R,T,U
Water consumption	C,D				H,L,I,U
Greenhouse gas (CO_2) emissions	A,B,C,D,E,F,H,J,L,M,N,O, R,S	F,H,L,R,S	F,R	A,S	F,G,H,I,L,P,R,S,T,U
Criteria air pollutants + VOC	A,B,C,E,H,J,L,M,R	H,L,R	R	A	H,L,R,T,U
Solid waste	B,C,H,J	H			H,U
Waste water	C,H,J				H,U
Toxic emissions	A,C,J,M			A	

A. (Boesch and Hellweg, 2010); B. (Huntzinger and Eatmon, 2009); C. (Marceau et al., 2006); D. (Josa et al., 2004; Josa et al., 2007); E. (Gabel and Tillman, 2005); F. (Flower and Sanjayan, 2007); G. (Cole, 1999); H. (Venta, 1999; Athena, 2005; Athena, 2010); I. (Marceau et al., 2007); J. (CEMBUREAU, 1999b); K. (Prusinski et al., 2004); L. (Lippiatt and Ahmad, 2004; Lippiatt, 2007); M. (Boesch et al., 2009); N. (Navia et al., 2006); O. (Lee and Park, 2005); P.(O'Brien et al., 2009); R. (Sjunnesson, 2005); S. (Collins, 2010); T. (Cazacliu and Ventura, 2010); U. (Jaques, 2001)

A.1.1. Synthesis and limitations of goal definition and scope of Cement LCAs.

Studies in this group are cradle-to-gate process LCAs with varying system boundaries and technological and geographical variations within their scopes. A synopsis of the cement LCA literature reveals that each of the Portland cement LCA studies, in itself has well defined scope and goal but each has its own limitations (See Table A-2).

Table A-2. Scope of Cradle-to-Gate Cement Production LCA

		Cement production processes						*Cement products*			
(Author, year)	*Region*	Extraction and crushing of raw materials	Raw meal preparation	Fuels and SCMs (e.g. waste tires, fly ash, slag) preparation	Pyroprocessing	Finish grinding and blending	Transportation (raw materials)	Clinker	Traditional PC	Blended cement	Other
(Boesch and Hellweg, 2010)	Switzerland; U.S.		*	*	*	*		*	*	*	
(Boesch et al., 2009)	Switzerland		*	*	*			*			
(Huntzinger and Eatmon, 2009)[2]	U.S.		*		*	*		*	*	*	*[1]
(Marceau et al., 2006)	U.S.	*	*		*	*	*	*	*		
(Navia et al., 2006)	Chile	*		*	*		*	*			
(Gäbel and Tillman, 2005)	Sweden	*	*	*	*	*	*	*	*		
(Josa et al., 2004)	Europe							*	*	*	

[1] PC with CKD and CO2 sequestered in CKD in cement

[2] LCI for only traditional Portland cement manufacturing but LCIA results are calculated for traditional PC, blended cement, cement with CKD, and cement with CO_2 sequestration

The Portland cement production takes place within a well-defined system boundary. Most cement LCA studies analyze major production processes with varying degrees of regional and technological details. However, the background system which supplies raw materials, additives, fuels, and electricity to the Portland cement plant expands the boundaries of the whole system. Introduction of alternative fuels (tires, solvents, municipal waste sludge, etc.) and supplementary cementitious materials (SCMs) into the cement making process as well as new technologies further complicate the analysis by and large. Some small nuances that are not captured in current cement LCAs as well as variations in those studies along with the underlying reasons worth mentioning here.

Noticeably, almost all cement studies focus on the most energy intensive stage of pyroprocessing (that is about 91% of total energy use). Extraction of raw materials is left out in more than half of the studies as it is either deemed insignificant in terms of energy consumption per tonne of cement (about 2% of total) or simply because of lack of data. Generally, 90% of cement raw materials (limestone, clay, marl, shale, etc.) are quarried. Particulate matter emissions, water consumption, water effluents, and use of explosives are major concerns during quarrying. For example, PM emissions from quarrying can cause about 89% of total particulates emissions from cement production process. Water consumption during quarrying is about 60% of the total use (Marceau et al., 2006). When we consider the global volumes of cement production (USGS 2009), the magnitude of impacts from quarrying can become significant. Similar arguments can be made for other cement production stages. Impacts from raw materials preparation, finish grinding and milling, and transportation stages are not considered in some of the cement production LCAs because energy use and environmental emissions during these stages are comparably low (2-5% of total production). However, as in the case of impacts from raw materials extraction, impacts from these three stages can add up to substantial amounts when in larger volumes.

In the table above, we observe a noticeable difference between scopes of two major cement production regions in the world, the U.S. and Europe. It is the consideration of fuels and alternative materials preparation process. European cement studies consider the electricity/energy use and related impacts during fuels and supplementary cementitious materials preparation process in their analysis (Gäbel and Tillman, 2005; Navia et al., 2006; Boesch et al., 2009; Boesch and Hellweg, 2010). The exclusion of this step in cement LCIs can lead to the underestimation of impacts from energy use during cement production processes. A quick calculation reveals the magnitude of the problem. For example, the most common type of fuel used in the U.S. cement kilns is coal. The U.S. cement industry's 65% of heat requirement is obtained from coal. As common practice, coal is ground before feeding into the kiln. Grinding of coal may require 30-40 kWh/tonne depending on the type of coal used in the kiln. According to USGS (2011), about 5.5 million tonnes of coal was used for clinker production in 2009. This corresponds to an average of 190 million kWh of annual electricity consumption during coal preparation process in the plant. The 2009 electricity consumption of U.S. cement industry was reported to be 9,020 million kWh. Assuming this number includes the electricity use for fuels preparation, about 2 percent of electricity consumption can be attributable to coal preparation. Waste fuels are also prepared before combusting in the cement kiln. The most common type of waste fuels is tires (supplies 4% of total U.S. cement kiln heat requirement) and shredding tires may require as much as 45 kWh/tonne (some cement kilns use whole tires while shredding may be required in others). When considered in global/national volumes, impacts from waste fuel preparation can be significant. These arguments are valid for preparation of other alternative materials used for supplementing cementitious materials. Before blending with clinker, such supplementary materials must be dried, ground, and prepared. In comparison to other mineral components, the preparation of GGBFS (ground granulated blast furnace slag) exhibits a higher environmental impact due to its additional grinding and drying requirement. Finally, studies fail to consider allocation of environmental impacts of such by-products among different product systems (e.g. fly ash from coal production vs. its use in cement production). Moreover, national LCI databases (e.g. NREL) do not provide LCIs of blended Portland cements, their production technologies, and supply chain impacts at all.

In summary, some studies limit their scope to one specific Portland cement production process while omitting others as in the case of (Boesch et al., 2009)'s focus on the clinker production. Others provide aggregated national LCIs for Portland cement production without the consideration of technological, geographical, and process-related details, e.g. (Josa et al., 2004; Josa et al., 2007). Time and data constraints are common sources of such limitations in Portland cement LCAs.

A.1.2. Synthesis and limitations of goal definition and scope of concrete and other concrete raw material LCAs. Table A-3 summarizes the reviewed concrete LCA studies. Concrete LCAs include environmental impacts from concrete batching, Portland cement and aggregates production whereas admixtures and water use are rarely analyzed. However, despite their inclusion in concrete LCIs, impacts from aggregates production show variations from one study to another. These differences are attributable to variations in selection of system boundary, type and hardness of aggregates processed, as well as variations in transportation modes and distances, electricity mix and so on. Since they are used in large amounts, the variations are suggested to be well-defined in aggregates LCA for accurate comparisons. USGS mineral industry surveys estimate 760 million tonnes of construction aggregates production in the United States in 2010 (USGS, 2011). Mining aggregates from bedrock (mostly from dry pits or quarries) generally requires drilling and blasting (use of dynamite). This first process breaks rock into a size that is suitable for transporting and crushing followed by repeated processes of screening, conveying, crushing, sorting, and washing (if necessary) until the proper sizes are reached. Natural sand and gravel may or may not be crushed depending on the size of the largest particle. In concrete LCAs, this distinction between crushed rock and natural sand and gravel is crucial. Major concerns regarding aggregate extraction and processing are changes to the landscape, PM emissions (from blasting, movement of excavation/drilling equipment, processing/crushing equipment, conveying, storing), resource depletion, water effluents (groundwater and surface water), as well as emissions from diesel fuel (during mining and transportation) and electricity use (during crushing, screening, sorting, and conveying). Energy consumption for aggregates varies from one aggregates production to another type (6-139 kWh/tonne or 0.022 to 0.5 MJ/tonne) (Langer, 2009). In concrete LCAs, impacts from aggregates production are accumulated covering activities from mining to processing at the crushing plant. LCI results are generally presented for the diesel fuel use and electricity use during aggregates production without process distinction.

Admixtures are generally excluded in concrete LCAs as they are used in small weight percentages (less than 1%) but when considered in national or global volumes their impacts can be considerable. According to the U.S. and European sources, it is estimated that 80% of concrete produced contains one or more types of admixtures (Mehta and Monteiro 2006; [BIBM] 2009). Of the different concrete admixtures, plasticisers and superplasticisers are the most widely used, representing approximately 80% of admixture consumption ([EFCA] 2006). In 2009, concrete production was 243 million tonnes in the U.S. and 377.4 million tonnes in Europe ([ERMCO] 2010). A simple back-of-an envelope calculation illustrates that about 3.24 kg of superplasticiser is required for one cubic meter of 35 MPa (with a unit weight of 2,370 kg/m^3) ready-mixed concrete, adding up to roughly 0.33 million and 0.51 million tonnes of plasticisers use annually in Europe and U.S., respectively. Environmental impacts from such large volumes need further investigation. As stated in (Forintek, 1993)'s research guidelines "…any material, no matter how small its mass contribution, which has extraordinary effects in its extraction, use or disposal… should be accounted for if it is an integral part of the product or essential to its production". Chemical admixtures may be a concern in regards to their toxicological properties (VOCs, heavy metals) during their production, application, and disposal. The waste disposal from the washing of ready-mix trucks could be a concern and impact of admixtures in the waste is not well-studied. Concrete admixtures have only been used for the last 30-40 years. For now, we can assume that so far demolished concrete has been free of admixtures. But in order to be able to estimate future emissions from the leaching of admixtures in concrete, tests can be carried out with defined admixture content. Knowledge/research gaps still exist in this ingredient of concrete compared to other constituents (Maeder et al., 2004).

Environmental impacts of form oils are generally ignored in concrete LCAs. According to (Glavind, 2009), hydrocarbons have been detected in concrete slurry from the rinsing of mixers, in concrete waste, and waste from demolished concretes. Such occasions can increase the risk of leaching of hydrocarbons to the groundwater. The major source of hydrocarbons is estimated to be the form oils used to grease the concrete mixers and mixer trucks. Typically, about 180 ml form oil/m^3 of concrete is used. Global concrete production is estimated to be about 25 billion tonnes annually based on ([IEA] and [WBCSD], 2009). For a typical unit weight of 2,370 kg/m^3 concrete, this translates into roughly 1.9 billion liters of form oil consumption which can have significant impacts on the environment.

Data for quantification of environmental impacts of water consumption during Portland cement and concrete production is another gap in the literature. The reason for lacking water data is the difficulty of capturing variations in water sources (such as how much of it is municipal water or recycled water from the concrete plant or storm water) as well as their use purposes during production (such as whether it is process water or non-process water, etc.)

In addition to the mentioned gaps in concrete LCAs, carbon (dioxide) uptake by concrete surfaces is not included within an LCA framework. Carbon uptake is defined as a mechanism that sequesters CO_2 released during the calcination of Portland cement products (Gajda and Miller, 2001). It is a diffusion- controlled process where carbonation occurs at the exterior surface and over time, moves towards the interior of the concrete. None of the current concrete and building LCA models considers carbonation process over the life cycle of concrete which would result in overestimation of net CO_2 emission results. Depending on the type of Portland cement binder and the application of recycled concrete aggregates during the secondary life, CO_2 emissions can be overestimated by about 13% to 48% without the consideration of carbon uptake (Collins, 2010). A complete environmental assessment of concrete requires the inclusion of carbon uptake during the use phase of buildings and impacts of carbon capture by recycled concrete aggregate use within the secondary life of buildings after demolishing. Despite the lack of LCAs with carbon uptake, there exists literature that presents the mechanism of both calcination vs. carbonation, carbonation rate from different concrete surfaces, and factors affecting it (Gajda and Miller, 2001; Kjellsen et al., 2005; Pommer and Pade, 2005; Pade and Guimaraes, 2007).

Table A-3. Scope of Cradle-to-Gate Concrete Rroduction LCA

		Concrete production processes						*Concrete products*			
(Author, year)	*Region*	Cement production	Fine aggregates production	Coarse aggregates production	Admixtures production	Concrete plant operations	Transportation	Concrete mixes with 100% PC	Concrete mixes with varying % slag	Concrete mixes with varying % of fly ash	Other
(O'Brien, Ménaché et al. 2009)	Australia	*	*	*			*	*	*		
(Flower and Sanjayan 2007)	Australia	*	*	*	*	*	*	*	*	*	
(Marceau, Nisbet et al. 2007)	U.S.	*	*	*		*	*	*	*	*	*[1]
(Sjunnesson 2005)	Sweden	*	*	*	*	*	*	*[2]			*[3]
(Marceau and VanGeem 2003; Prusinski, Marceau et al. 2004)	U.S.	*	*	*		*	*	*	*	*	*[4]
(Jaques 2001)	New Zealand	*	*	*		*	*	*			*[5]

[1] Concrete masonry block and precast concrete mixes (reinforcing steel impacts excluded)

[2] Ordinary PC concrete with the addition of superplasticizers

[3] Frost-resistant concrete with the addition of superplasticizers and air-entraining admixtures

[4] Precast concrete = mixes with silica fume in addition to slag and PC (reinforcing steel impacts excluded)

[5] Concrete masonary, cement mortar, and precast concrete units (reinforcing steel included)

A.1.3 Life cycle inventory representation in cement LCAs. Energy consumption in Portland cement production has been studied extensively in the literature. However, a detailed analysis reveals a number of gaps even in this highly covered area of cement LCI. Energy consumption data are aggregated into national averages in most of the Portland cement LCAs (Josa et al., 2004; Marceau et al., 2006; Boesch et al., 2009; Huntzinger and Eatmon, 2009; Boesch and Hellweg, 2010). Regional and technological variations in Portland cement production are mostly underrepresented. For example, none of the studies give details about the fuel mix used for pyroprocessing and electricity production specific to the region where Portland cement production takes place. Some Portland cement plants in the U.S. use imported clinker, which is later on ground with gypsum to produce domestic Portland cement or import Portland cement itself. Portland cement and clinker imports constitute about 8 percent of the total U.S. consumption in 2009 (van Oss, 2010). However, none of the LCAs considers the upstream profile of the imported clinker and the corresponding energy use factors specific to the country of origin as well as the transportation impacts of such imported clinker. They, instead, as in the example of (Marceau et al., 2006) study, assume domestic and imported clinker to be produced by similar technologies. For a realistic and accurate environmental assessment, these energy-related limitations should be addressed in new Portland cement LCA models.

As consequence of intensive energy use, cement industry is a major contributor to greenhouse gas emissions. According to the European Commission's IPPC report, other key emissions are particulate matter (PM), nitrogen oxides (NOx), and sulfur dioxide (SO_2) ([IPPC], 2009). Additionally, carbon monoxide (CO), volatile organic compounds (VOC), and toxic emissions (e.g. heavy metals, dioxins and furans) may be of concern. Type and amount of air pollutants vary with the composition of raw materials and fuels used in Portland cement making process, as well as the choice of manufacturing technology and other parameters.

For cement production, major sources of CO_2 emissions are the calcination of carbonate minerals in the raw feed and the combustion of fuels. Generally, most studies assume that calcination CO_2 is derived from $CaCO_3$. According to the IPCC methodology (2009), it is reasonable to look just at $CaCO_3$ and to ignore the effects of other carbonates. Calcination CO_2 can be reduced by the substitution of traditional raw materials with non-carbonate sources of CaO. However, GHG and other organic emissions may increase in cases where the coprocessed alternative raw materials have higher contents of organic matter than the traditional raw materials.

Computation of CO_2 emissions from fuel combustion in the kiln needs further analysis and can vary considerably because of the variations in the quantities, heat contents, fuel carbon factors, and compositions of kiln fuels, kiln burning conditions, type and age of kilns, emission control technologies and other factors. But in most cement LCAs, carbon dioxide emissions for the pyroprocessing stage are generally based on the national averages for the fuel composition and kiln technologies without consideration of the above mentioned factors and different technology and material options. None of the LCA studies consider coprocessing of fossil and biogenic wastes. Fuel based-CO_2 can be reduced by coprocessing fossil and biogenic wastes. Fossil wastes generally feature lower CO_2 emission factors than traditional fuels, and CO_2 emissions from the combustion of biogenic wastes are biogenic and hence not accounted for (in contrast to the emissions for the preparation and transport of these wastes). Further GHG emission reductions occur in the resource supply chain since less fuel needs to be produced and transported. As opposed to reduced GHG emissions and resource consumption, the coprocessing of waste may increase the input of heavy metals into the kiln system leading to increased air emissions and elevated heavy metal concentrations in the product.

Additionally, organic carbon in raw materials as well as calcination of dust leaving the kiln system are two other sources of CO_2 from raw materials but are rarely considered in Portland cement LCAs. CO_2 from non-kiln fuels which include those used during raw materials drying (but drying of kiln fuels is considered as part of the kiln fuel consumption), room heating and cooling, operation of the plant equipment and on-site vehicles are not taken into consideration. CO_2 emissions from the transportation of raw materials, fuels, products as well as their distribution within the system also require assessment ([CSI], 2005; van Oss, 2005).

Particulate matter (PM) is generated during almost all stages of Portland cement production process (Venta, 1999; Athena, 2005; Athena, 2010). Two of the U.S. Portland cement LCAs (Marceau et al., 2006; Huntzinger and Eatmon, 2009) tabulate PM emissions for major processes; including raw meal preparation, pyroprocessing, and finish grinding. Additionally, (Marceau et al., 2006) present PM emissions from quarrying activities and transportation of raw materials to the Portland cement plant.

Organic carbon content in natural raw materials can cause elevated hydrocarbon (HC) and carbon monoxide (CO) emissions. In addition to three Portland cement LCAs (Nisbet et al., 2002; Gabel and Tillman, 2005; Boesch et al., 2009), other sources including (Venta, 1999; CEMBUREAU, 1999a; CEMBUREAU, 1999b; Greer and Hawkins, 2004; Athena, 2010) provide information on emissions of HCs from Portland cement manufacturing. Hydrocarbon emissions from Portland cement pyroprocessing are mostly composed of volatile organic compounds (VOC) and methane (CH_4) (Marceau et al., 2006). Emissions of VOCs and other HCs from Portland cement production are generally at insignificant levels. (CEMBUREAU, 1999a) explains why these pollutants are at such low levels as: "...other substances entering the kiln system which could give rise to undesirable emissions are either effectively destroyed in the high temperature combustion process or almost completely incorporated into the product."

In literature, a number of Portland cement LCA and non-LCA studies provide data for toxic emissions of VOC, benzene, dioxin/furans, heavy metals (Ar, Cr, Pb, Hg, Ni, Thallium, Zn), HF, and HCl as part of their environmental analysis (CEMBUREAU, 1997; CEMBUREAU, 1999a; CEMBUREAU, 1999b; Greer and Hawkins, 2004; Gabel and Tillman, 2005; Marceau et al., 2006; Navia et al., 2006; Boughton, 2007; Richards et al., 2008a; Richards et al., 2008b; Boesch et al., 2009). Looking at the data sources, one can conclude that those Portland cement LCAs which focus on alternative/waste raw materials and fuels also provide toxic air emissions in their LCIs as it is one of the concerns for using such materials. Waste used as alternative fuel or as a substitute for raw material may contain varying concentrations of trace elements. Certain conditions, such as burning waste fuels in an inefficient wet kiln, can result in higher toxic emissions. For example, in (Boesch and Hellweg, 2010) study, elemental analysis of scrap tires, solvents, and waste oils show considerably higher amounts of Zn, Pb, Cr, Cd, and other trace elements compared to other traditional fuels. Although some studies were conducted on the criteria pollutant and hazardous air pollutant (HAP) emissions associated with tire-derived fuel, these studies (Richards et al., 2008a; Richards et al., 2008b) examine fuels that are a combination of scrap tires and conventional fuels. Therefore, these studies do not isolate the criteria pollutant or HAP emissions associated with scrap tires alone ([USEPA], 2011) and the LCI results can be misleading. For an accurate assessment, fuel burning and air control technologies need to be taken into consideration while calculating emissions from kilns.

Solid and water waste from cement production is rarely included in cement LCIs (Table 3-7). Portland cement kiln dust (CKD) and used refractory lining are major sources of solid waste. (Huntzinger and Eatmon, 2009) provide background information on total CKD generation, recycling rates, and its use in Portland cement kilns while (Marceau et al., 2006) present the average amount of CKD generated per tonne of Portland cement produced in the U.S. and how much of it is landfilled versus recycled in other applications. Additionally, (CEMBUREAU, 1999b) compares solid waste generation from traditional Portland cement kilns with the Portland cement kilns burning waste fuels. Major liquid effluents are suspended solids, aluminum, phenolics, oil and grease, nitrate/nitrite, dissolved organic compounds, chlorides, sulfates, sulfides, ammonia/ammonium, phosphorus, and zinc. Known sources of these effluents consist of waste water from non-contact cooling of equipment and cooling of Portland cement directly after finish milling process. Runoff from Portland cement plant during storms, quarry de-watering, CKD landfill wells and pile runoff also contribute to waste water generation. Based on the data in Table A-2), the literature on solid and water waste is evidently insufficient.

Table A-4. Environmental Inventory Metrics Captured by Cradle-to-Gate Cement Production LCAs.

(Author, year)	*Energy consumption*	*Water consumption*	*Greenhouse gases, calcination*	*Green house gases, process /fuel*	*Green house gases, total*	*NOx*	*SOx / SO_2*	*CO*	*VOC*	*Particulate matter (PM)*	*Toxic air emissions*	*Water emissions*	*Solid waste*	*Notes*
Cement production														
(Boesch and Hellweg, 2010)	*		*	*	*	*	*	*	*	*	*			Toxic air emissions: HCl, Hg, PAH, PCDD/F, heavy metals
(Boesch et al., 2009)	*		*	*	*	*	*	*	*	*	*			
(Huntzinger and Eatmon, 2009)	*				*					*			*	Solid waste: CKD
(Marceau et al., 2006)	*	*			*	*	*	*	*	*	*	*	*	Toxic air emissions: HCl, Hg, NH_3, PCDD/F Solid waste: CKD
(Navia et al., 2006)	*				*						*			Toxic air emissions: heavy metals (limited to Cr, Pb, Zn)
(Gäbel and Tillman, 2005)	*			*	*	*	*	*	*	*				
(Josa et al., 2004)	*	*			*	*	*			*				
(O'Brien et al., 2009)					*									

(Flower and Sanjayan, 2007)					*									
(Marceau et al., 2007)	*	*			*	*	*	*	*	*	*	*	*	Based on (Marceau et al., 2006)
(Sjunnesson, 2005)	*				*	*	*	*		*		*		Water emissions: oils, phenols, COD, Tot-N, Tot-P
(Marceau and VanGeem, 2003; Prusinski et al., 2004)	*				*	*	*	*	*	*			*	Solid waste: CKD; for both PC and slag cement
(Jaques, 2001)	*				*	*	*	*	*	*				

A.1.4. Life cycle inventory representation in concrete and its raw material LCAs.

Environmental impacts associated with concrete and its other raw materials production are mostly attributed to electricity and diesel fuel use.

A summary of LCI representation for concrete LCAs is provided in. Except for two Australian LCAs that focus solely on GHG emissions (Flower and Sanjayan, 2007; O'Brien et al., 2009) from concrete production, all other concrete LCAs provide energy consumption data. Energy consumption from ready-mixed concrete plant operations constitute about 4% of the embodied energy of concrete (Marceau et al., 2007). At the concrete plant, electricity and fuel are required for mixing, conveying, pumping of concrete mix and its materials as well as heating/cooling of the facility. The energy use in the concrete plant is very much dependent on the electricity-grid mix within the region. Major concerns regarding concrete plant operations are most relevant to waste products. Such as rejected batches, excess production, recycled aggregate from concrete waste, the technology for using the waste water from washing and mixing and their environmental impacts.

Greenhouse gas emissions are well covered in all concrete and its raw material LCAs. Criteria air pollutants are also analyzed by various LCA and non-LCA sources (Venta, 1999; Jaques, 2001; Lippiatt and Ahmad, 2004; Prusinski et al., 2004; Athena, 2005; Sjunnesson, 2005; Lippiatt, 2007; Marceau et al., 2007). Table A-5 demonstrates that SO_2, NOx, and CO emissions are covered well in literature. Roughly 70 to 90 percent of these three emissions are attributable to the Portland cement production (Marceau et al., 2007). Although U.S. PCA's Portland cement-related NOx percentages coincide with those of Canadian ATHENA tool (Venta, 1999), SO_2 and CO emissions from Portland cement production and concrete processing add up to 80 to 90 percent (each contribute 30 to 50 percent depending on the region, concrete mix, etc.) of total emissions (Venta, 1999). PM and VOC emissions are also included in concrete LCAs (Table 3-8). About 60 to 80 percent of total particulate matter is observed from Portland cement production processes while concrete batching is responsible for roughly 10 to 20 percent of all. VOC emissions from Portland cement production constitute approximately 30 percent based on (Venta, 1999) and 60 percent (Marceau et al., 2007) of total emissions while 20 to 30 percent of VOC is allocated to mainly concrete batching activities.

Some concrete LCAs (Prusinski et al., 2004; Marceau et al., 2007; Sjunnesson, 2005; Jaques, 2001), in addition to the BEES tool by (Lippiatt and Ahmad, 2004; Lippiatt, 2007) examine toxic emissions of heavy metals, dioxins and furans, and other carcinogens associated with the production of concrete and its raw materials (Portland cement, SCMs, fine and coarse aggregates). (Prusinski et al., 2004) specifically provide the emissions from the manufacturing and transportation of slag Portland cement concrete. Volatile matter (mostly from additives in concrete) and organic substances that are emitted during or shortly after the concrete manufacturing processes need further attention, especially those concrete products with chemical admixtures (Kuhlman and Paschmann, 1996).

Three of the concrete LCAs provide solid waste data in their concrete production inventories (Jaques, 2001; Prusinski et al., 2004; Marceau et al., 2007). Solid wastes are generated during Portland cement production (mostly in the form of CKD), as well as during processing of aggregates and SCMs, and concrete batching processes. According to the ATHENA tool (Venta, 1999; Athena, 2005; Athena, 2010), quarrying aggregates is similar to quarrying Portland cement raw materials in terms of wastes produced. Moreover, solid waste from concrete processing include mixer washout, sludges from settling basins and ponds, and returned excess ready-mixed products unless reprocessed. Currently, solid wastes can be disposed in one of the three ways: backfilling into quarries, long-term storage on-site, and reprocessing. Specifically, there is lack of data about disposal rates of solid wastes, as well as their constituents which vary considerably with concrete mix design and concrete ingredients. Further research is required for this category of concrete LCI data.

Liquid effluents associated with concrete production are analyzed in three groups: effluents from Portland cement production, effluents from aggregates production, and effluents from concrete manufacturing. They include aluminum, ammonia (-um), COD, chlorides, copper, DOC, iron, nitric, nitrites, oil and grease, pH, phenolics, phosphorus, sulfates, sulfides, suspended solids, water that leaves site, and zinc. Two of the concrete LCAs (Sjunnesson, 2005; Marceau et al., 2007) include releases to water in concrete life-cycle inventories. Additionally, a non-LCA study by (Kuhlman and Paschmann, 1996) specifically focuses on leaching from both ready-mixed and precast concrete through life-cycle stages of concrete from raw materials extraction to its disposal/reutilization. During processing of ready-mixed concrete, the leaching of environmentally significant substances is of major concern. The source of this concern is predominantly the alkalis which contain traces of heavy metals (Pb, Cd, Cr, Hg, thallium, and Zn) as well as organic constituents in the additive agents and additional organic compounds found in concrete. This study shows that, except for chromium (Cr), leaching of other heavy metals is not to be expected to occur due to their low solubility in the alkaline medium of ready-mixed concrete. Throughout the concrete use phase, leaching of heavy metals and organic constituents from conventional concrete are shown to be extremely low. During the end-of-life stage, leaching of environmentally significant contaminants is not expected from crushed concrete.

Results from the investigated studies demonstrate that concrete is an environmentally compatible material through all its life-cycle phases but there is still a need for further investigation of its environmental impacts, especially, toxic emissions to air, water, and land in addition to energy use input and GHG and criteria air pollutants within an LCA context.

Table A-5. Environmental Inventory Metrics Captured by Cradle-to-Gate Cement Production LCAs

(Author, year)	Energy consumption	Water consumption	Green house gases, process	NOx	SOx / SO_2	CO	VOC	Particulate matter (PM)	Toxic air emissions	Water emissions	Solid waste	Notes
Fine and coarse aggregates production												
(O'Brien et al., 2009)		*	*									
(Flower and Sanjayan, 2007)			*									
(Marceau et al., 2007)	*		*	*	*	*	*	*	*	*	*	Toxic emissions: HCl, Hg, NH_3, PCDD/F, heavy metals Solid waste: other
(Sjunnesson, 2005)	*		*	*	*	*				*		Water emissions: oils, phenols, COD, N, P
(Marceau and VanGeem, 2003; Prusinski et al., 2004)	*		*	*	*	*	*	*				
(Jaques, 2001)	*							*				
Admixtures production												
Flower and Sanjayan, 2007)	*		*									
Sjunnesson, 2005)	*		*	*	*	*						
Concrete plant operations												
(Flower and Sanjayan, 2007)			*									
(Marceau et al., 2007)	*	*	*	*	*	*	*	*	*	*	*	
(Sjunnesson, 2005)	*		*	*	*	*		*				
(Marceau and VanGeem, 2003; Prusinski et al., 2004)	*	*	*	*	*	*	*	*	*	*	*	Toxic emissions: H_2S and metals; Water emissions: COD, suspended solids; Solid waste: Slag reject (for slag cement concrete only)
(Jaques, 2001)	*	*	*	*	*	*	*	*	*		*	

A.1.5. Life cycle impact assessment representation in cement and concrete LCAs.

Concrete LCAs lack the LCIA step whereas cement LCAs include the LCIA step generally. Due to lack of information and data for LCIA, this LCA step is not covered extensively in most of the studies. The tables above provide some of the impact measures (inventories) used in both cement and concrete LCAs. In most of these studies, it is not clear, for example, how toxic emissions are translated to impact categories like human toxicity or damage to human health. On the other hand, global impacts such as GWP or climate change can be modeled with well-studied GHG gases. The regional impact category such as acidification (in SO_2 equivalent) potential can also be modeled with well-inventoried NOx and SO_2 emissions which are commonly included in most cement and concrete LCAs. In addition to NOx and SO_2 while some studies consider HCl, ammonia (NH_3) emissions others do not include these emissions in developing acidification impact categories. In case of eutrophication, NOx is the major source during cement manufacturing. Again as in the case of acidification, other relevant sources of eutrophication such as NH_3, total nitrogen (N-tot), and chemical oxygen demand (COD) are omitted in some LCIs of cement while others include them. Such inconsistencies in development of impact values would cause unequivalent comparison of results. Other less studied impact categories such as human toxicity, eco toxicity, and resource consumption are developed using different classification and characterization methods and factors. While one study (Navia et al., 2006) applies damage-oriented impact assessment methodology, others (Josa et al., 2007; Huntzinger and Eatmon, 2009; Boesch and Hellweg, 2010) limit LCIA to midpoint (that provides only characterization factors but no damage assessment). Midpoint analysis is based on traditional LCIA characterization and normalization methods as indicators located between inventory interventions and endpoint effects and damages. Midpoint analyses reduce the amount of assumptions and the complexity of the modeling and results in comparison with endpoint analyses. However, they make the interpretation of absolute results more difficult since they do not refer directly to the damages produced (Josa et al., 2007). In (Navia et al., 2006), for example, damage to health is related to the categories of carcinogens, respiratory organics and inorganics, climate change, radiation, and ozone layer.

One important problem with human toxicity and eco toxicity categories is the lack of exposure data – from one study to another human / environment exposure to pollutants vary considerable depending on the proximity, concentration of pollutant, existence of other sources of pollutant as well as regional differences in climate, geography, population density and so on. It would be good to report results in ranges of possible values. Additionally, due to lack of information about chemical composition of some common air pollutants from cement manufacturing (PM, HC, VOC, etc.), it is almost impossible to categorize some pollutants provided in the inventory in terms of their toxicity, carcinogenicity, and bioaccumulation and so on. Impacts from heavy metals and other toxic emissions are mostly omitted in LCIA since their quantities are deemed insignificant however it’s their severity that could be of significant in terms of damage to human and environment.

A.2. Wood Literature Review

In an attempt to further understand the environmental impacts of wood construction materials, the existing LCA literature has been organized and compared in terms of life cycle inventory (LCI), and life cycle impact categories. This section provides a critical review of the existing literature related to life-cycle assessment (LCA) applied to wood-based construction and materials. The existing literature recognizes the major cradle-to-grave life cycle phases to be: extraction of raw materials, processing raw materials, construction of building system, occupation and maintenance of built environment, demolition/ deconstruction of building system, disposal or reuse of materials, and transport at appropriate stages. This synthesis reveals data gaps, universal areas of uncertainty, and opportunities for further research.

Many of the collected studies diverge in their definition of scope, life cycle phase inclusion, or base assumptions. This creates a challenge for comparing buildings or systems. Especially as these wood products are compared with their steel or concrete alternatives, researchers must choose to consider functional units wisely. Wall systems may be compared by either their thermal or structural properties. While ‘square feet of a wood framed building’ are popular functional units, many materials may supply structural, mechanical, and thermal systems in a single built environment. The material selection of the structural or enveloping systems also affects the expected building lifespan, challenging scientists to find more appropriate methods to compare different materials.

The review finds that LCAs on wood construction and construction materials is an expanding, but still limited research topic in literature. Furthermore, the existing body of work exhibits methodological incompatibilities that serve as barriers to the widespread utilization of LCA by policy makers. While material-based life cycle assessment stipulates cradle to grave evaluation, few studies on wood-based structures have considered all phases. Gaps in data availability and phase representation should be resolved before an accurate comparison of construction material life cycle impacts is achieved.

A.2.1. Critical Review of Wood-Based Construction LCA Literature. The literature review focuses on 30 peer reviewed journal articles which concentrate on LCA of wood construction materials and components. These studies represent over 20 years of LCA research, and follow the ISO 14040 framework as a guideline for systematic analysis ([ISO] 2006). While over 100 wood-related environmental impact reports were collected in the literature review, less than 50 had a clearly thorough conformance to ISO 14040 standards. These 50 were narrowed to 30 principal analyses based on accessibility and scope of work. The review found a wide range in the years and locations of study, the building types, methodologies, and functional units of the investigations. The assembled literature encompasses raw material harvest, processing, wood based construction and end of life scenarios. Many of the reviewed LCAs include life cycle comparisons to other common construction materials (Cole 1998; Börjesson 2000; Lenzen 2002; Gustavsson 2006a; Gustavsson 2006b). Phase representation and included inventory and assessment categories vary considerably throughout the literature. Despite conformance to ISO 14040 guidelines, these incongruities no doubt affect the comparability of results. The objective of the critical review will be to better understand the existing literature and to identify research gaps that deserve further investigation to develop wood LCA literature.

A.2.2. Data sources and availability. In a compilation of over 30 life cycle analyses related to wood-based construction, a third of these studies trace data from Buchanan and Honey's *Energy and Carbon Dioxide Implications of Building Construction* (Buchanan 1994). Furthermore, Buchanan and Honey's "New Zealand Energy Coefficients of Building Materials" are primarily sourced (with minor additions) from a study by Baird and Chan "who estimated the energy requirements for all major building materials, and for house construction in New Zealand" (Baird 1983). Besides the fact that so many reports are mining the same data source, it is also notable that these data already 27 years old and still being cited in the recent literature (Cole 1996; Buchanan 1999; Börjesson 2000; Venkatarama Reddy 2003; Gustavsson 2006a; Gustavsson 2006b; Dimoudi 2008; Salazar 2009; Gustavsson 2010; Werner 2010).

A.2.3. Years of study. The Consortium for Research on Renewable Industrial Materials (CORRIM) was founded in 1976 to expand upon a report by the National Academy of Science to inform policymakers of the implications of decisions that affect the forestry and wood manufacturing industries. As energy analysis methodologies were refined for the manufacturing industries, embodied energies of construction materials could be calculated (Baird 1983). This data allowed for the estimated of embodied energy in buildings (Cole 1992; Cole 1996; Buchanan 1999) and the comparison of wood with other structural materials (Koch 1992; Börjesson 2000). Further research proposed ways that wood-based construction could mitigate climate change (Börjesson 2000; Sathre 2009; Sathre 2010), especially as it related to replacing or disposing of materials (Thormark 2001; Thormark 2006; Upton 2008; Blengini 2009; Dodoo 2009). Controversies in methodological approach have expanded the discussion to consider the cut-off effects of process LCA versus input-output LCA (Lenzen 2002). The amalgamation of such efforts has lead to change-oriented conclusions (Halliday 1991; Petersen 2005; Haapio 2008) and even country-wide impact assessment profiles (Koch 1992; Skog 2008; Werner 2010). The unmistakable growth in the wood construction material data and LCA sources is illustrated in **Error! Reference source not found.**. The figure represents 117 studies which have added to the knowledge-base for wood construction material environmental impact. The 30 major LCA studies are shown in light blue. Peaks occurring in 2004 and 2010 represent the publication of the 12 CORRIM Phase 1 Final Report Modules and the CORRIM publications in *Wood and Fiber Science*, respectively.

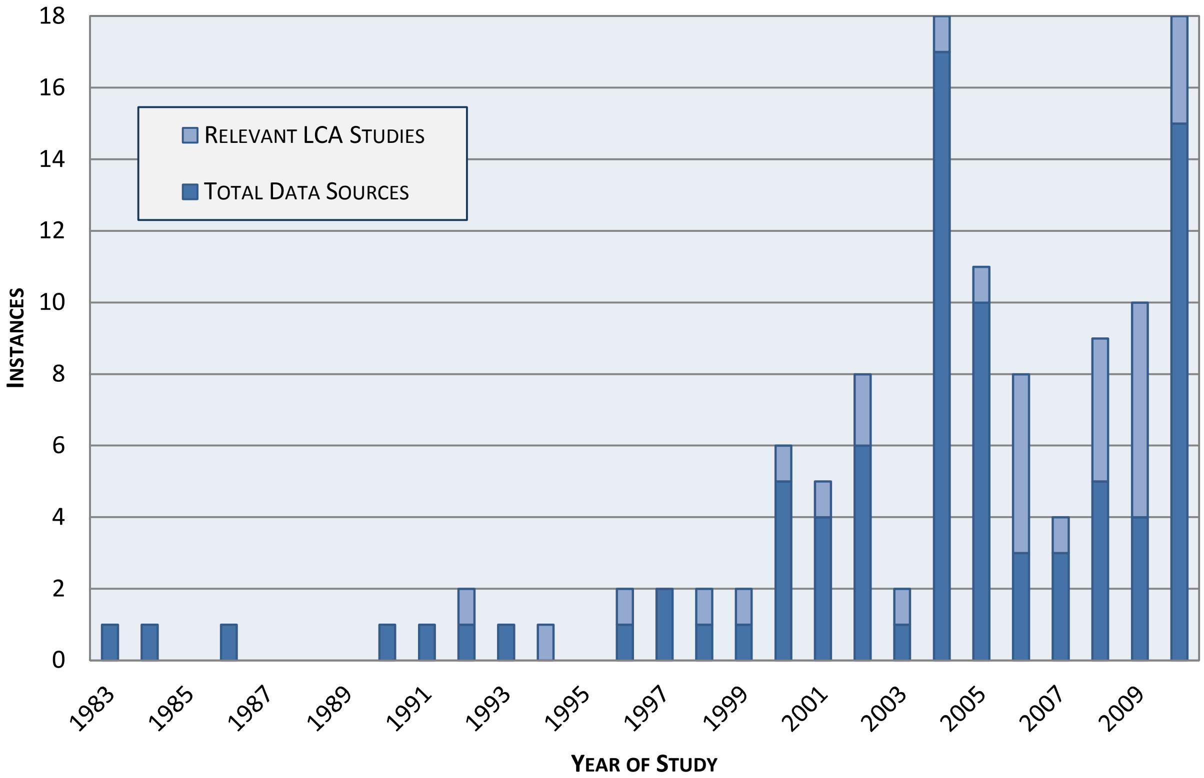

Figure A-1. Wood construction materials- data and LCA sources by year.

A.2.4. Locations of study. Though the 30 primary LCA studies that were critically reviewed represent a wide range of countries (see **Error! Reference source not found.**) , many of the LCAs that were analyzed stem from northern Europe, as wood is a prevalent building material, but building codes have not allowed wood to replace concrete or steel in tall buildings. Of the 14 which are based in Sweden, at least five study the Wälludden building (Börjesson 2000; Lenzen 2002; Gustavsson 2006a; Gustavsson 2006b; Dodoo 2009). This 1190 m^2 4-story apartment building was one of the first wooden-framed buildings in Sweden after the building code changed in 1994 to allow wood buildings to be taller than two stories (Gustavsson 2006b). The United States may be underrepresented here since the CORRIM studies were not all included in the critical review. The 2004 report which compared wood, concrete, and steel framed houses in Minneapolis and Atlanta were part of over thirty published CORRIM reports between 2004 and 2010 (Lippke 2004). All thirty reports were not critically reviewed, as the methodology is consistent, and the studies tend to focus on very specific wooden components (e.g. laminated veneer lumber (Wilson 2005), glulam (Puettmann 2005), particleboard (Wilson 2010a), fiberboard (Wilson 2010b), hardwood flooring (Hubbard 2010), etc.).

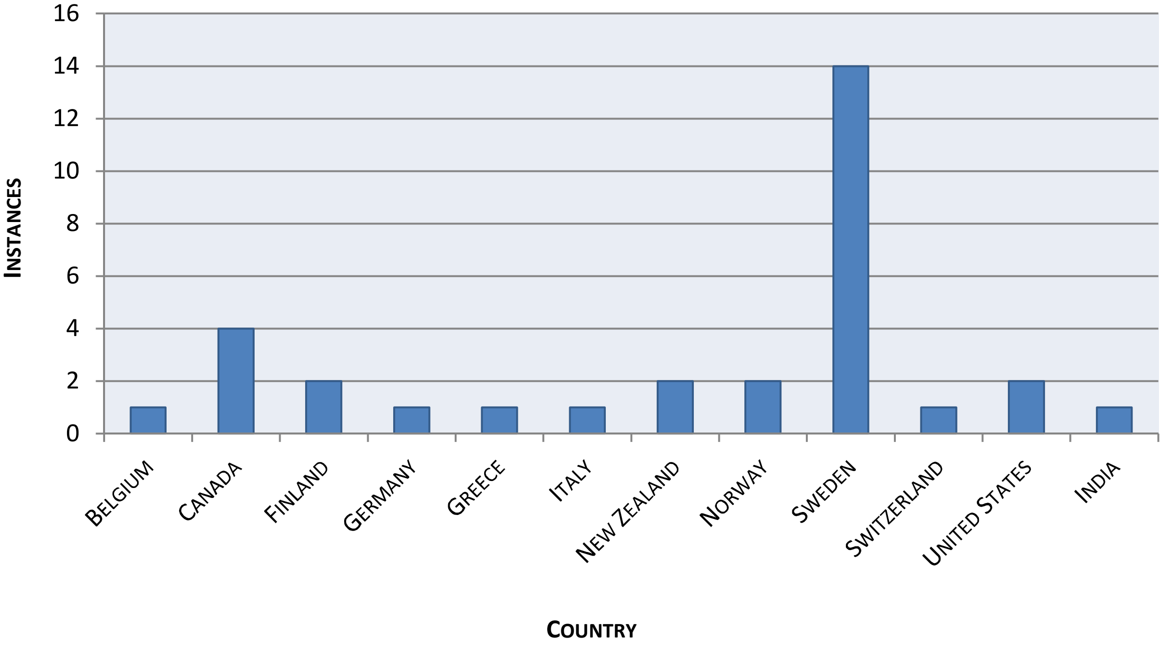

Figure A-2. Country representation.

A.2.5. Comparison of goal definitions and scope. ISO 14040 requires a clear goal and scope definition which specifies the intended application of the LCA, including the product to be studied, functional unit, system boundaries, etc. Most of the studies claim to be cradle to grave process LCAs with varying temporal boundaries for the studied structures. Yet only about a third (10 of the 30 investigations) include life cycle inventory assessment (LCIA) as part of the study. Due to data availability, most researchers roughly estimate select inventories, such as CO_2 emissions or energy use, and present those limited results.

A detailed review of the analyses' scopes showed that all but two studies utilized the process LCA methods. Nässén et al. compared their top-down economic input-output results with 18 bottom-up studies to compare estimated primary energy use and CO2 emissions (Nässén 2007). Nässén's results compared with those from Lenzen et al. whose hybrid LCA approach also showed the process LCA methods to significantly underestimate energy use and CO2 emissions (Lenzen 2002).

The collection contains a variety of functional units. Ten of the 30 studies measured the environmental impact over the functional unit of one building, given its square footage, number of stories, and lifespan. Similarly, eleven LCAs estimated the impact per square meter, which can then be extrapolated to calculate the environmental impact of the whole building. The remaining studies utilized functional units which were based on weight, volume, or the given dimensions of one structural component.

Certain studies identify the building type in the scope, especially if the authors aim to make assumptions for energy use during the operational phase. Within the sample set, 15 of the 20 buildings were residential, either as single family homes or as apartment buildings. Only two of the LCAs considered office buildings (Cole 1996; Dimoudi 2008). This may be directly related to the prevalence of which structures are designed with wood joists and beams. Typically wood framed construction is not chosen for office buildings, which require large open spaces. Still, one study did examine the embodied energy and GHG savings by replacing steel beams with glulam beams in Gardermoen Airport (Petersen 2002).

The typical assumed building or structural component lifespan must also be defined to confine the temporal boundary, especially if the operational phase will be examined. Figure shows that 50 and 100 years are the most frequently assumed life spans in the LCA literature, though some studies may consider as few as 25 years, or as many as 160 years. Certain LCAs compare the environmental impact of the functional unit over variable life spans to determine how service life affects the inventory. In one such case, Haapio, et al. consider the environmental effects of various combinations of cladding, window, and roofing systems with 60, 80, 100, 120, 140, and 160 year life expectancies (Haapio 2008). The life span decision greatly impacts results of an LCA, especially if use-phase emissions are considered. “For short life-spans, the recurring embodied energy is less than the initial energy and for long-life buildings (say 100 years), the recurring embodied energy is between two and three times greater” (Cole 1996). Therefore, in all LCAs which reported the life expectancy of the building, care was taken to justify this critical assumption.

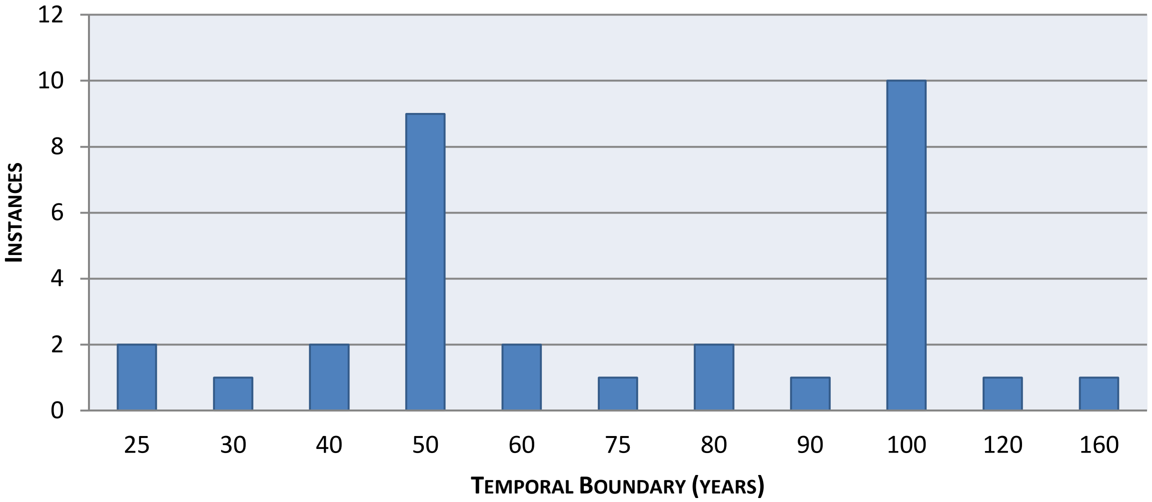

Figure A-3. Typical assumed building/ component lifespan.

Table A-6. Review of Study Scopes

Author	Year	Country	Type of LCA	Functional Unit	Building Type	Lifespan (years)
Gustavsson	2010	Sweden	Process	One apartment building	Apartment	50, 100
Kellenberger	2009	Sweden	Process	1 square meter of opaque building component with similar heat transfer rate	N/A	80
Nebel	2006	Germany	Process	1 square meter of laid wood floor covering	N/A	50
Verbeeck	2010	Belgium	Process	Building materials: kg, m3, m2, m. System components: kW	Residential	30, 60, 90
Upton	2008	United States	Process	1.5 Million Residential Houses	Residential	100
Nässén	2007	Sweden	Input-Output	Square Meter	Residential	50
Blengini	2009	Italy	Process	1 square meter over 1 year	Residential	40
Gustavsson	2006a	Sweden	Process	One apartment building	Apartment	100
Salazar	2009	Canada	Process	One residential house	Residential	100
Haapio	2008	Finland	Process	One residential house	Residential	60, 160
Lenzen	2002	Sweden	Hybrid	Walludden Building	Apartment	50, 100
González-García	2009	Sweden	Process	One cubic meter of fresh wood under bark	N/A	N/A
Petersen	2002	Norway	Process	.14 Cubic Meters	Airport	50
Werner	2010	Switzerland	Process	One Cubic Meter of Wood	N/A	N/A
Sathre	2009	Sweden	Process	One Building	Apartment	N/A
Dodoo	2009	Sweden	Process	One apartment building	Apartment	100
Cole	1998	Canada	Process	Various Structural Assemblies	All	N/A
Börjesson	2000	Sweden	Process	Walludden Building	Apartment	50, 100
Buchanan	1999	New Zealand	Process	Square Meters	Various	40
Petersen	2005	Norway & Sweden	Process	Various Structural Assemblies	N/A	N/A
Dimoudi	2008	Greece	Process	Square Meters	Office	50
Buchanan	1994	New Zealand	Process	Square Meters	Various	25
Cole	1996	Canada	Process	Square Meters	Office	25, 50, 100
Thormark	2006	Sweden	Process	Square Meters	Apartment	50
Venkatarama Reddy	2003	India	Process	Square Meters	N/A	N/A
Cole	1992	Canada	Process	kg	N/A	N/A
Thormark	2001	Sweden	Process	Ton	N/A	N/A
Lippke	2004	United States	Process	One residential house	Residential	75
Sathre	2006	Sweden	Process	kg	N/A	N/A
Gustavsson	2006b	Finland & Sweden	Process	Square Meters	Apartment	100

A.2.6. Article categorization. The reviewed articles can be categorized based on their primary theme, whether that is to compare wood to other structural materials, to expand upon one phase in the life cycle, or to compare methodological variability. Twenty of the analyses were change oriented LCAs which compared wood with steel, concrete, brick, etc. Of these, there were 16 comparisons with concrete, 11 with steel, and 2 with aluminum and masonry. A number of analyses compared wood with multiple other materials, as can be seen in

Table and Figure A-4. Six reports concentrate on end of life scenarios which include landfilling, recycling, reusing, and sometimes combustion with energy recovery (Thormark 2001). The 'method comparison' category is reserved for those reviews which investigate process LCA methodology, whether to assess traditional methods (Lenzen 2002), use an input-output approach (Nässén 2007), or call for more stringent comparison with economic models (Petersen 2005). Still, others were written with a focus on forestry (Börjesson 2000; Lippke 2004; Werner 2010), or the transportation of wood products (González-García 2009). It is clear from the review that most of the studied LCAs compare the inventory or assessment results of wood products with those of other comparable materials, mainly steel and concrete.

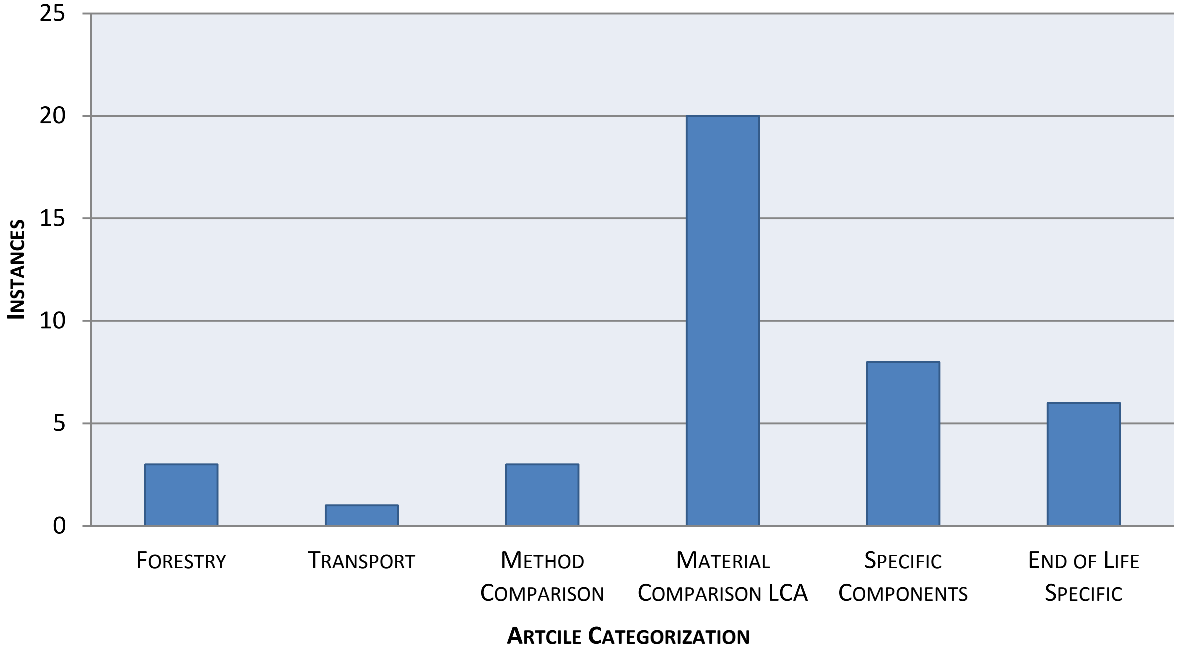

Figure A-4. Review of article categorization.

Table A-7. Review of Article Categorization

Author	Year	Article Categorization					
		Forestry	Transport	Method Comparison	Material Comparison LCA	Specific Components	End of Life Specific
Gustavsson	2010					√	
Kellenberger	2009					√	
Nebel	2006					√	
Verbeeck	2010					√	
Upton	2008				√ (S, C)		
Nässén	2007			√			
Blengini	2009						√
Gustavsson	2006a				√ (C)		
Salazar	2009				√ (V)		
Haapio	2008					√	
Lenzen	2002			√	√ (C)		
González-García	2009		√				
Petersen	2002				√ (S)	√	
Werner	2010	√					
Sathre	2009				√ (C)		
Dodoo	2009				√ (C)		√
Cole	1998				√ (S, C)	√	
Börjesson	2000	√			√ (C)		√
Buchanan	1999				√ (S, C, A)		
Petersen	2005			√	√ (S, C)	√	
Dimoudi	2008				√ (S, C)		
Buchanan	1994				√ (S, C, A)		
Cole	1996				√ (S, C)		
Thormark	2006				√ (V)		√
Venkatarama Reddy	2003				√ (S, C, M)		
Cole	1992				√ (S, C, M)		
Thormark	2001				√ (V)		√
Lippke	2004	√			√ (S, C)		
Sathre	2006						√
Gustavsson	2006b				√ (C)		

(C): Concrete (S): Steel (M): Masonry (A): Aluminum (V): Various

A.2.7. Phase representation. While life cycle assessments are intended to consider a product from cradle to grave, limitations in data sources, time, or scope of study may reduce the number of included phases. A critical review of the literature shown in Figure and Table A-8 confirm that cradle to site phases are highly studied, mainly due to the availability of embodied energy data from manufacturing processes and transportation. Harvest is almost always considered, since many LCAs depend on the carbon sequestration credits of the wood sources. Depending on the scope of the study, some LCAs truncate the material life and only consider primary embodied energy of the structural system, not the energy used by the building itself during operation (Buchanan 1999). Studies which consider end-of-life scenarios (recycling, reuse, landfilling, energy conversion, etc) tend to do so exclusively (Thormark 2001; Dodoo 2009; Werner 2010). Others indicate that demolition and end of life energy can be ignored, as they tend to contribute insignificantly to the total life cycle energy (Börjesson 2000; Adalberth 2001). Still, the use phase and specifically maintenance and renovation phase are clearly underrepresented in the literature. Especially with wood products, where the life expectancy is commonly 50 to 100 years, there should be some consideration for the maintenance of such components. Change oriented or comparative LCAs typically exclude the use phase and maintenance and renovation phase since they are assumed to be comparable between structures of different materials (Upton 2008). Authors should strive to be most clear in defining which phases are considered, and justification should be given for those which are ignored. For example, inclusion of the transportation phase was frequently not stated or not transparently summarized in the reviewed literature. Only one of the thirty studies clearly considered all phases.

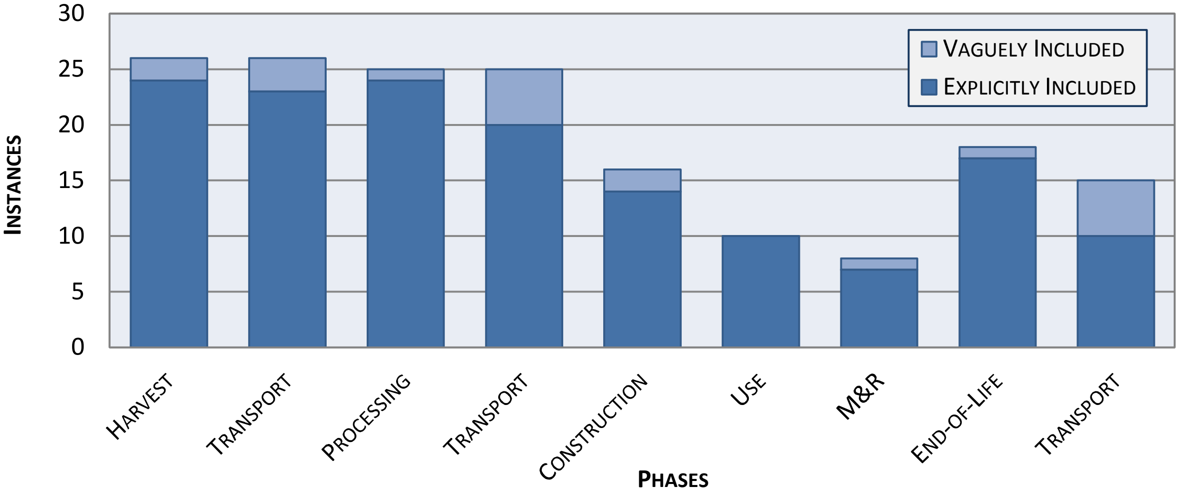

Figure A-5. Phase representation in the literature

Table A-8. Review of Phase Representation

		Phases								
Author	Year	Harvest	Transport	Processing	Transport	Construction	Use	M&R[1]	End-of-Life	Transport
Gustavsson	2010	X	X	X	X	X	X	NO	X	X
Kellenberger	2009	X	X	X	X	X	X	X	X	X
Nebel	2006	X	X	X	X	X	NO	X	X	X
Verbeeck	2010	X	X	X	X	?	X	X	NO	
Upton	2008	X	X	X	X	X	NO	NO	X	?
Nässén	2007	X	X	X	X	X				
Blengini	2009	X	X	X	X	X	X	NO	X	X
Gustavsson	2006a	X	X	X	X					
Salazar	2009	X	X	X	X	X		X	X	X
Haapio	2008	?	?	X	?	X	X	X	X	?
Lenzen	2002	X	X	X	X				X	X
González-García	2009		X							
Petersen	2002	X	X	X	?	NO	NO		X	X
Werner	2010	X							X	
Sathre	2009	X	?	X	?	X	NO		X	?
Dodoo	2009	?	?	?	?	?			X	?
Cole	1998				X	X				
Börjesson	2000	X	X	X	X	NO	NO	NO	X	NO
Buchanan	1999	X	X	X	X		NO			
Petersen	2005									
Dimoudi	2008	X	X	X			X			
Buchanan	1994	X	X	X	?		X			
Cole	1996	X	X	X	X	X	X	X	NO	NO
Thormark	2006	X	X	X	X	NO	X	X	X	NO
Venkatarama Reddy	2003	X	X	X	X	X				
Cole	1992	X	X	X	X	X				
Thormark	2001								X	X
Lippke	2004	X	X	X	X	X	X	?	?	?
Sathre	2006	X	X	X	X				X	X
Gustavsson	2006b	X	X	X	X				X	X

[1] Maintenance and Renovation

X: Explicitly Included

?: Vaguely Included

NO: Explicitly Not Included

A.2.8. Life cycle inventory representation. The literature was surveyed for inventories which recorded raw materials, energy use, fuel use, water use, GHG emissions, other criteria air pollutants, solid wastes, water wastes, and toxic emissions. Many of the embodied energy and

GHG emissions estimations have been sourced exclusively from two popular data sources: Buchanan and Honey and Baird and Chan (Baird 1983; Buchanan 1994). These original and then updated energy coefficients for building materials make inventorying energy and GHGs very straightforward. Still, other inventories are significantly underrepresented, as displayed in Figure A-6 and Table A-9.

Table A-9. Review of Life Cycle Inventory Representation

The literature overwhelmingly depended on energy use and GHG emission inventories, and many studies simply reported embodied energy or embodied carbon without developing an impact assessment (Cole 1992; Buchanan 1994; Cole 1996; Buchanan 1999; Thormark 2001; Venkatarama Reddy 2003; Sathre 2006; Thormark 2006; Gustavsson 2006a; Gustavsson 2006b; Nässén 2007; Dimoudi 2008; Upton 2008; Sathre 2009; Gustavsson 2010; Werner 2010).

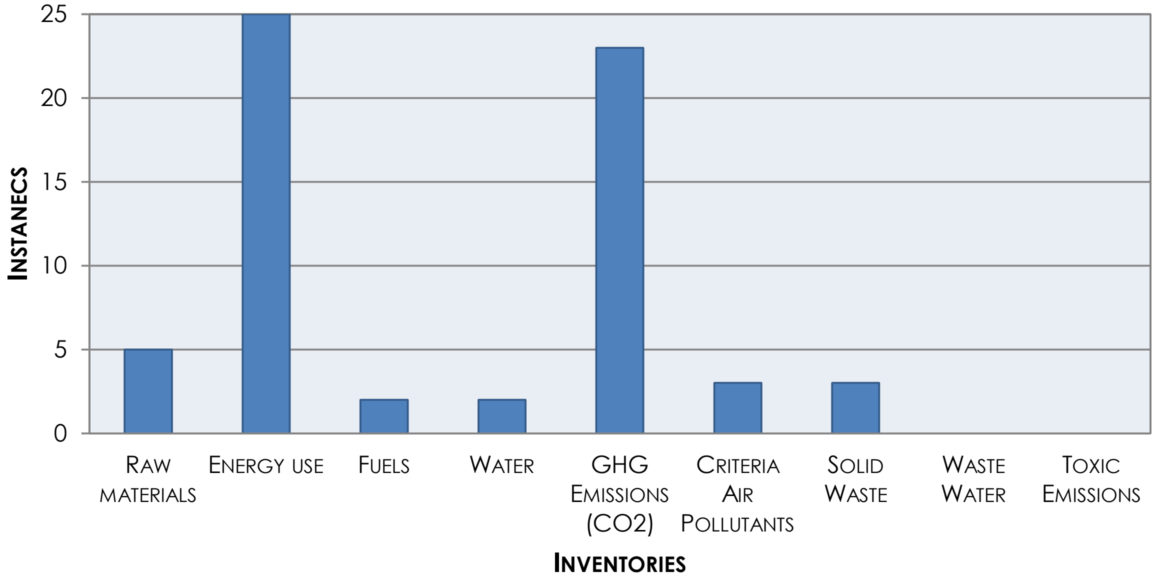

Figure A-6. Life cycle inventory representation in the literature.

A few studies were more comprehensive in their inventories. Haapio included raw material usage (kg), energy use (MJ), pollutants to water (indexed), GHGs (indexed), and solid wastes (kg) for various cladding, window frame, and roofing materials with varying life expectancies (Haapio 2008). Lippke's CORRIM study included the same inventories as Haapio, and compared houses in Minneapolis and Atlanta. Here, the data was sourced from, and consequently helped to develop, SimaPro software and the ATHENA Environmental Impact Estimator model (EIE) (Lippke 2004). Kellenberger's study of building components accounted for solid waste and raw material flows during construction and also renovation (Kellenberger 2009). When wood transportation models are the focus, the fuel usage is accounted for (González-García 2009).

Still, the underrepresentation of inventory flows such as waste water or toxic emissions points to a lack of data or research in these fields. These should be considered in future LCAs of wood products as “the environmental impacts from sites handling wood include emissions of particles and volatile organic compounds from wood, emissions from the use of energy fuels, release of storm water that has been in contact with wood or irrigation water used to protect wood, and emissions and spillages from machines and vehicles used at the site” (Hedmark 2008). Material makeup, specifically wood preservatives, has the largest effect on acidification, eutriphication, human toxicity, and photochemical ozone emissions. Wood may leach these chemicals through contact with soil, for example, or emit them when burnt. Further, disposal of wood products is shown to knowingly influence life cycle effects for many wood-based products, which is especially detrimental if wood is landfilled (Petersen 2005).

Table A-9. Review of Life Cycle Inventory Representation

		Life Cycle Inventory								
Author	Year	Raw materials	Energy use	Fuels	Water	GHG Emissions (CO2)	Criteria Air Pollutants	Solid Waste	Waste Water	Toxic Emissions
Gustavsson	2010		X			X				
Kellen-berger	2009	X	X					X		
Nebel	2006	X	X			X				
Verbeeck	2010		X			X				
Upton	2008		X			X				
Nässén	2007		X			X				
Blengini	2009	X								
Gustavsson	2006a		X			X				
Salazar	2009			X		X				
Haapio	2008	X	X		X	X	X	X		
Lenzen	2002		X			X				
González-García	2009		X	X		X				
Petersen	2002		X			X				
Werner	2010					X				
Sathre	2009		X			X				
Dodoo	2009		X			X				
Cole	1998		X			X				
Börjesson	2000		X			X				
Buchanan	1999		X			X				
Petersen	2005									
Dimoudi	2008		X			X				
Buchanan	1994		X			X				

Cole	1996		X							
Thormark	2006		X							
Venkatarama Reddy	2003		X							
Cole	1992		X			X	X			
Thormark	2001		X							
Lippke	2004	X	X		X	X	X	X		
Sathre	2006		X			X				
Gustavsson	2006b					X				

A.2.9 Life cycle impact assessment representation. The purpose of an LCI is to collect the inputs and outputs for a product or service. This inventory can be used to calculate and interpret the potential environmental impacts associated with the functional unit throughout its life cycle ([ISO] 2006). Figure A and Table A-10 show that only 14 of the reviewed studies carried out a detailed impact assessment. The review found the following impact assessment categories represented in the literature: land use, eco-toxicity, human toxicity, photo-oxidant formation, eutrophication, acidification, ozone depletion, depletion of raw materials including fossil fuels, and global warming potential.

Global warming potential was clearly the most commonly assessed impact, likely due to the accessible data on embodied energy and carbon of construction materials, and the recent status of global climate change. GWP therefore becomes an easily calculated and understandable metric over which material alternatives may be compared. Still, it is notable that more studies did not consider land use impacts, since forests cover hundreds of acres for significant timeframes. The articles which do consider land use impacts handle it by allocating a certain amount of 'surplus forest' to the concrete or steel framed building. This assumption that each alternative has the same access to land area equalizes the system boundaries by assigning a credit for the extra carbon sequestered by non-harvested trees (Dodoo 2009). Of course, when considering land use, the building's life span and the acreage of forest land needed are key variables. Also, end-of-life considerations, such as burning, re-use, or landfilling of demolition materials can significantly impact the GHG mitigation and land use efficiency of the structure (Börjesson 2000). Therefore, the need for a land use impact assessment would be determined based on the system boundaries of the study.

Studies which do estimate and interpret environmental impact often cite the program or method used for these calculations. Kellenberger uses the Eco-indicator 99 method to model the effects of resource use and emissions on human health, ecosystem quality, etc. (Kellenberger 2009). The minimal emphasis on eco-toxicity, POCP, eutrophication, and acidification points to the lack of data and inventorying of polluted runoff.

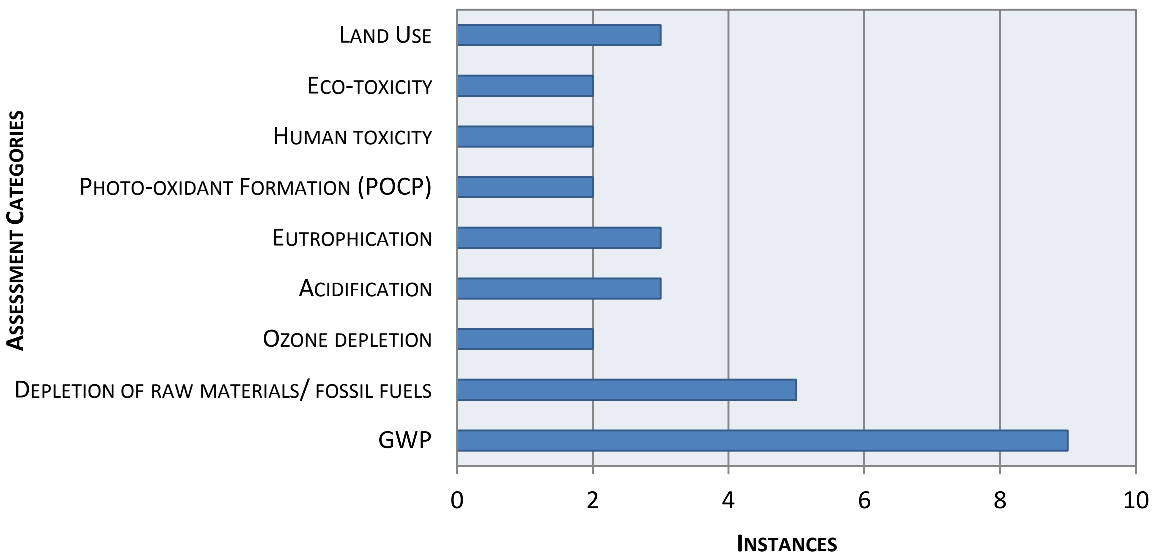

Figure A-7. Life cycle impact assessment representation in the literature.

Table A-10. Life Cycle Impact Assessment Representation in the Literature

Author	Year	Life Cycle Impact Assessment								
		GWP	Depletion of raw materials/ fossil fuels	Ozone depletion	Acid-ification	Eutro-phication	Photo-oxidant Formation (POCP)	Human toxicity	Eco-toxicity	Land Use
Gustavsson	2010									
Kellenberger	2009		X					X	X	
Nebel	2006	X		X	X	X	X			
Verbeeck	2010	X								
Upton	2008									
Nässén	2007									
Blengini	2009	X	X	X	X	X		X	X	
Gustavsson	2006									
Salazar	2009		X							
Haapio	2008	X	X							
Lenzen	2002	X								
González-García	2009	X	X		X	X	X			

Petersen	2002	X								
Werner	2010									
Sathre	2009									
Dodoo	2009									X
Cole	1998	X								
Börjesson	2000									X
Buchanan	1999									
Petersen	2005									
Dimoudi	2008									
Buchanan	1994									
Cole	1996									
Thormark	2006									
Venkatarama Reddy	2003									
Cole	1992									
Thormark	2001									
Lippke	2004	X								
Sathre	2006									X
Gustavsson	2006									

A.2.10. Discussion and conclusion. The literature review uncovered a number of trends and gaps in the LCAs to date which consider wood building products. Certainly data availability affects the opportunities for the research community to analyze and compare products. The fact that many papers tend to cite the same primary data source (Baird 1983) should be noted as a potential limiting factor to the knowledge generated in subsequent studies. There is a clear need for current regionally specific data when compiling life cycle inventories. In all phases, especially manufacturing and processing, technology resolution should be represented in the data to assure more exact inventories.

The review has shown that most studies only inventory energy and carbon dioxide as a measure for greenhouse gases. Furthermore, very few studies utilize these inventories for a detailed impact assessment, even in terms of global warming potential. There is a significant inconsistency in the assumption of building lifespan, as the review showed a range of 135 years. This assumption critically influences the relative impact of primary embodied energy versus operational energy. This criterion also significantly affects maintenance and renovation considerations, especially considering the variation in durability between wood, concrete, and steel.

It has been shown that many studies truncate product life, or choose to ignore certain life cycle phases. The definition of scope and system boundaries must not exclude critical phases if product inventories and impact assessments are meant to compare alternative products. Of course, this requires the availability of regional datasets for all phases of construction materials from cradle to grave. Common methods for estimating inventories for underrepresented phases should be established. This especially applies for construction and maintenance and renovation. For the use phase, operational modeling tools such as eQUEST can be leveraged to provide critical data. This also suggests that more research is necessary to compare end-of-life scenarios for wood and other construction materials in order to produce a dataset to be utilized in LCA.

These gaps in data availability and phase representation must be resolved before accurate comparison of construction material life cycle impacts is achieved. While material-based life cycle assessment stipulates cradle to grave evaluation, few studies on wood-based structures have considered all phases. There must be a distinction in the LCA community, and especially the literature, between life cycle analyses and life cycle *phase* analyses, as many studies tend to neglect phases which may be complicated to model. Currently, cradle to site phases (harvest, manufacturing, transport) are widely considered, but few studies account for the operational or maintenance and renovation phases. Allocation assumptions, land use consequences, and end-of-life alternatives have been shown to drastically affect the results of the comparative studies (Gustavsson 2006b). Common methodologies should be established to conventionalize the field, and uncertainty analyses should be applied to bound the results.

A.3. Steel Literature Review

Table A-11. Summary of Inventory Data Availability by Major Steel Making Process and Key Inputs and Outputs

Sinter Making	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19	20	21	22	23	30	31	33	36	37	38	39	46	47
Inputs																														
Raw materials				x	x				x	x		x				x						x								
Energy and fuels		x	x	x	x	x		x	x		x		x	x		x		x			x	x	x				x	x		
Water					x								x			x									x					
Outputs																														
Greenhouse gases					x	x			x				x			x					x	x	x				x			
Criteria air pollutants				x	x		x		x				x			x	x		x				x		x		x			
Solid waste				x	x								x			x														
Wastwater				x	x								x			x			x											
Toxic emissions				x	x											x	x		x			x								

Blast Furnace	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19	20	21	22	23	30	31	33	36	37	38	39	46	47
Inputs																														
Raw materials	x			x	x				x	x	x	x				x	x	x				x								
Energy and fuels		x	x	x	x	x		x	x		x		x	x	x	x		x			x	x	x				x	x		
Water					x				x				x			x									x					
Outputs																														
Greenhouse gases					x	x			x				x		x	x					x	x	x				x	x		
Criteria air pollutants				x	x		x		x				x			x	x		x				x		x		x			
Solid waste				x	x								x			x			x											
Wastwater				x	x				x				x			x			x											
Toxic emissions				x	x											x			x			x								

Basic Oxygen Furnace	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19	20	21	22	23	30	31	33	36	37	38	39	46	47
Inputs																														
Raw materials	x			x	x				x	x	x	x				x	x	x				x		x						
Energy and fuels		x	x	x	x	x		x	x		x			x		x	x	x			x	x	x				x	x		
Water					x				x				x			x									x					
Outputs																														
Greenhouse gases					x	x			x				x		x	x				x	x	x	x				x	x		
Criteria air pollutants				x	x		x		x				x			x	x		x				x		x		x			
Solid waste				x	x								x			x			x											
Wastwater				x	x				x				x			x			x											
Toxic emissions				x	x											x	x		x			x								

Direct Reduced Iron	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19	20	21	22	23	30	31	33	36	37	38	39	46	47
Inputs																														
Raw materials	x			x	x				x	x	x	x				x	x	x												
Energy and fuels		x	x	x	x	x		x	x		x		x	x		x		x			x		x				x	x		
Water					x				x				x			x									x					
Outputs																														
Greenhouse gases						x							x		x	x					x		x				x	x		
Criteria air pollutants				x			x						x			x	x						x		x		x			
Solid waste				x									x			x														
Wastwater				x									x			x														
Toxic emissions				x												x														

Electric Arc Furnace	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19	20	21	22	23	30	31	33	36	37	38	39	46	47
Inputs																														
Raw materials	x			x	x				x	x	x	x				x	x	x	x			x		x						x
Energy and fuels		x	x	x	x	x		x	x		x		x	x	x	x	x	x			x	x		x						x
Water					x				x				x			x									x					
Outputs																														
Greenhouse gases					x	x			x				x		x	x			x	x	x	x	x				x	x		
Criteria air pollutants				x	x		x		x				x			x	x		x				x		x		x			
Solid waste				x	x								x			x			x											
Wastwater				x	x				x				x			x			x											
Toxic emissions				x	x											x	x		x			x								

Rolling and Finishing	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19	20	21	22	23	30	31	33	36	37	38	39	46	47
Inputs																														
Raw materials	x			x	x				x	x	x	x				x	x					x		x			x			
Energy and fuels		x	x	x	x	x		x	x		x	x	x	x	x	x	x	x			x	x	x				x			
Water					x				x							x									x		x			
Outputs																														
Greenhouse gases					x	x			x				x		x	x					x	x	x				x			
Criteria air pollutants				x	x		x		x				x			x	x						x		x		x			
Solid waste				x	x								x			x			x											
Wastwater				x	x				x				x			x			x											
Toxic emissions				x	x											x	x		x			x								

Table A-12. Summary of LCIA Studies of Steel Production by Major Steel Making Process and Impact Category

Study #	1	2	4	30	36	37
Mining						
GWP					x	x
Ozone			x			
Land use					x	x
Human and ecotoxicity	x					
Eutrophication	x				x	
Coke Making	1	2	4	30	36	37
GWP						
Ozone			x			
Land use						
Human and ecotoxicity	x					
Eutrophication					x	
Sinter Making	1	2	4	30	36	37
GWP	x			x	x	x
Ozone						
Land use						
Human and ecotoxicity		x		x		
Eutrophication					x	
Iron Making	1	2	4	30	36	37
GWP	x			x	x	x
Ozone			x			
Land use						
Human and ecotoxicity	x			x		
Eutrophication	x				x	
Basic Oxygen Furnace	1	2	4	30	36	37
GWP	x			x	x	x
Ozone			x			
Land use						
Human and ecotoxicity	x			x		
Eutrophication	x				x	
Direct Reduced Iron	1	2	4	30	36	37
GWP	x				x	x
Ozone			x			
Land use						
Human and ecotoxicity	x					
Eutrophication					x	
Electric Arc Furnace	1	2	4	30	36	37
GWP	x			x	x	x
Ozone	x					
Land use						
Human and ecotoxicity	x			x		
Eutrophication	x				x	
Rolling and Finishing	1	2	4	30	36	37
GWP	x			x		
Ozone			x			
Land use						
Human and ecotoxicity	x			x		
Eutrophication	x				x	

Table A-13. Collection of Studies and Data Sources Assessed for Steel Production, with Study Number

1	Junnila, S., Horvath, A. (2003) Life-Cycle Environmental Effects of an Office Building. Journal of Infrastructure Systems. pp. 157-166
2	Cole, R. J., Kernan P.C. (1996) Life-Cycle Energy Use in Office Buildings. Building and Environment, Vol. 31, No. 4. pp. 307-317
3	Venkatarama Reddy, B.V., Jagadish, K.S. (2003). Embodied Energy of Common and Alternative Building Materials and Technologies. Energy and Buildings 35. pp. 129-137.
4	Horvath, A., hendrickson, C. (1998) Steel Versus Steel-Reinforced Concrete Bridges: Environmental Assessment. Journal of Infrastructure Systems. pp.111-117.
5	U.S. Department of Energy. (August 2000). Energy and Environmental Profile of the U.S. Iron and Steel Industry. DOE/EE-0229.
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