May 2017

Reducing the Environmental Impacts of Building Materials: Embodied Energy Analysis of a High-performance Building

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REDUCING THE ENVIRONMENTAL IMPACTS OF BUILDING MATERIALS:
EMBODIED ENERGY ANALYSIS OF A HIGH-PERFORMANCE BUILDING

by

Layla Qarout

A Dissertation Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

in Architecture

at

The University of Wisconsin-Milwaukee

May 2017

Abstract

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The University of Wisconsin - Milwaukee, 2017
Under the Supervision of Professor Michael Utzinger

The purpose of this research was to assess the embodied energy and carbon emissions of structural building materials, and determine environmental savings associated with construction. In common architectural practice, the analysis of the environmental cost of materials is typically not taken into account. This can be attributed to the lack of available data, loyalty to conventional construction methods, and complexity of embodied energy calculations. Although efforts are made to ensure accuracy of the information contained in energy databases, they are based on public domain sources and the "best" energy and carbon coefficients, with no guarantee to accuracy. Therefore, it is critical to develop new methods to accurately assess embodied energy and CO_2 emissions of building materials. The need for this assessment is tied to the development of high-performance buildings that integrate and optimize energy efficiency and life cycle performance; shifting the focus to the reduction of building operational energy makes embodied energy a significant part of a building's life cycle.

This dissertation takes a case study approach focused on the assessment of the embodied energy of the structural materials and photovoltaic system of a high-performance building. This approach facilitated a detailed calculation of the selected materials' environmental costs, achieving accurate results in comparison with publicly available databases.

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Acknowledgments

I would like to express my appreciation and gratitude to my advisor Professor Michael Utzinger for the continuous support, for his patience, motivation, and immense knowledge. Without his encouragement and supervision, this dissertation would not have taken shape. My sincere thanks to committee members Brian Schermer, Kurt Zimmerman and James Wasley, for their contribution to the direction and richness of this research. I would also like to express my gratitude to Joel Krueger, project architect at the Kubala Washatko Architects, Buddy Huffaker, director, and Steve Swenson, ecologist, at the Aldo Leopold Foundation for their time, and for providing me access to information that facilitated my research.

Last but not least, I would like to express my deepest appreciation to my Grandparents Ali and Badiaa Saffarini , my Mom Daad, my Sister Sahar, and my family for their continuous love and support. They gave me the strength and confidence to achieve my goals.

1 Research Motivation

1.1 Introduction

The negative impact of human activities on our environment is arguably one of the most pressing problems that we face today. These activities are amplified by the increased demand for agricultural land fueled by the recent explosion of the human population and increased urbanization. Subsequently, there is growing demand for construction at the expense of natural resource coupled with an increasingly accelerating pace of technological progress in the building industry, both of which adversely contribute to ecosystem health. To realize the effect of building construction and operation on the environment, we must consider the total life cycle energy of buildings. This energy is comprised of embodied and operational energy, with the latter contributing a larger proportion of the total building life cycle energy.

A focus on building construction and its role in reducing operational energy led to the development of high-performance buildings, which support environmentally responsible and resource-efficient building design that aims to reduce greenhouse gas emissions and other negative environmental impacts, particularly those associated with the design and operation of buildings. As the operational energy requirements and CO_2 emissions of high-performance buildings drop, the embodied energy and CO_2 emissions due to building construction become a more significant part of the life cycle building energy and CO_2 emissions costs. Embodied energy for conventional buildings represents between 2% - 38% of the energy use over their lifetime periods. This increases to 9% - 46% for high-performance buildings and 100% for zero carbon ones, making embodied energy a significant part of the total life cycle energy of a building (Cole et al, 1996). Therefore, accounting for embodied energy of construction materials is fundamental to the understanding of

the implications due to material selection in building design.

1.2 Background

Terminology like sustainable design did not exist in the past; low technology construction and limitations of transportation naturally fostered architecture based on climate and regional sources. In the 19th century mankind connected technical knowledge to the discovery of natural resources for energy production. Inventions such as the steam engine for example, enabled mass production at unprecedented speeds. Industrialization resulted in huge amounts of resource consumption producing carbon emissions. Resources used during that period were non-renewable fossil fuels such as coal and oil. The amount of resource consumption initiated during the industrial revolution surged over time; the number of factories increased along with living standards and the negative impact on the environment. In the 20th century new processes and inventions were made to ensure comfort and establish convenient living conditions. At this time the atmosphere indicated

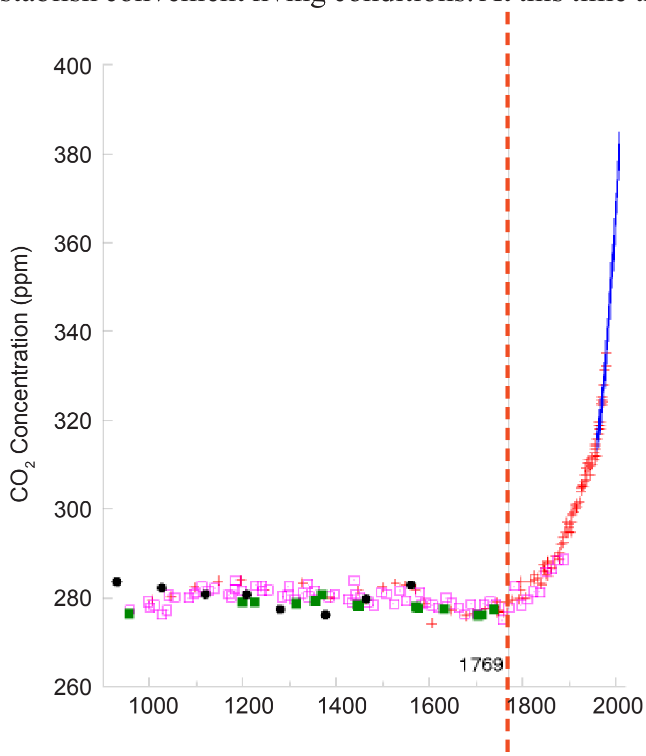


Figure 01: CO_2 Concentrations (parts per million) for the last 1,100 yrs
Source: withouthotair.com

signs of changing conditions, CO_2 levels increased by 35% from 1880 (Intergovernmental Panel on Climate Change (IPCC), 2007). Today, the obsession with the application of high technology continues without critical examination of its effects. This caused a spike in fossil fuel energy consumption, leading to an alarming increase in greenhouse gas emissions and other negative environmental impacts. Figure 01 shows measurements of the carbon emission concentrations in the atmosphere from 1000AD to the present.

In the U.S., 45% of CO_2 emissions are associated with the building sector (Figure 02). Looking at global resource consumption and CO_2 emissions, the building industry contributes a significant share; 50% of the resources are consumed and 60% of global waste is produced from this sector (Hegger et al., 2007). The extracted resources are either manufactured to become a

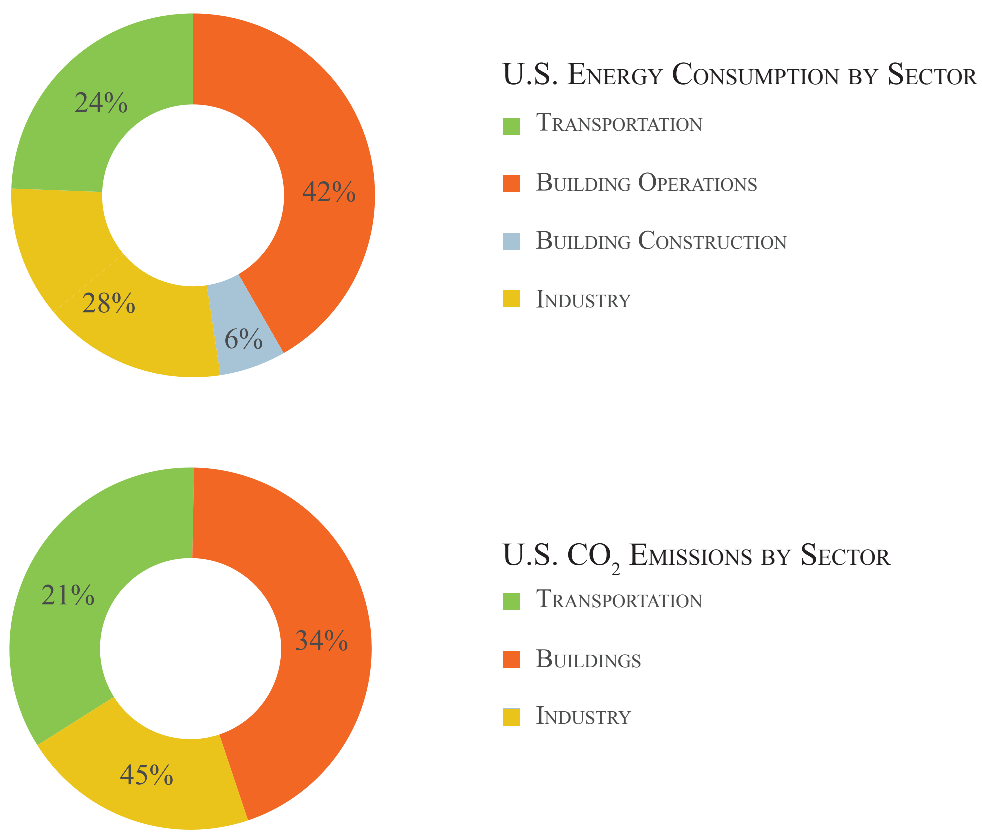


Figure 02: U.S. Energy Consumption and CO_2 Emissions by Sector
Source: By Author based on U.S. Energy Information Administration (2012)

component that is part of the building, or are used in the energy generation process. Commonly used materials such as reinforced concrete for example, is widely used all over the world due to its durability, availability, and conventional construction methods. Yet the production of cement (main component of concrete) is an energy-intensive process; for each one-ton cement produced, 930 kg CO_2 is emitted. This relationship between building construction and resource consumption became noticeable in the 1970s as a result the oil embargo in 1973-74 (Hildebrand, 2014), creating an awareness on the dependence on resource imports which in turn led to a number of regulations aiming at the reduction of resource consumption. An early example is the *"Warmeschutzverdnug"* in Germany (BGBI, 1976); a regulation started in 1976 focusing on the reduction of operational energy of buildings. Another example is the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE), which has been regulating indoor comfort since and striving to lower operational energy of buildings since 1973. The following chart (Figure 03) shows a 45% reduction of the operational energy of buildings designed to meet ASHRAE codes over a 30 year period (from 1980-2010).

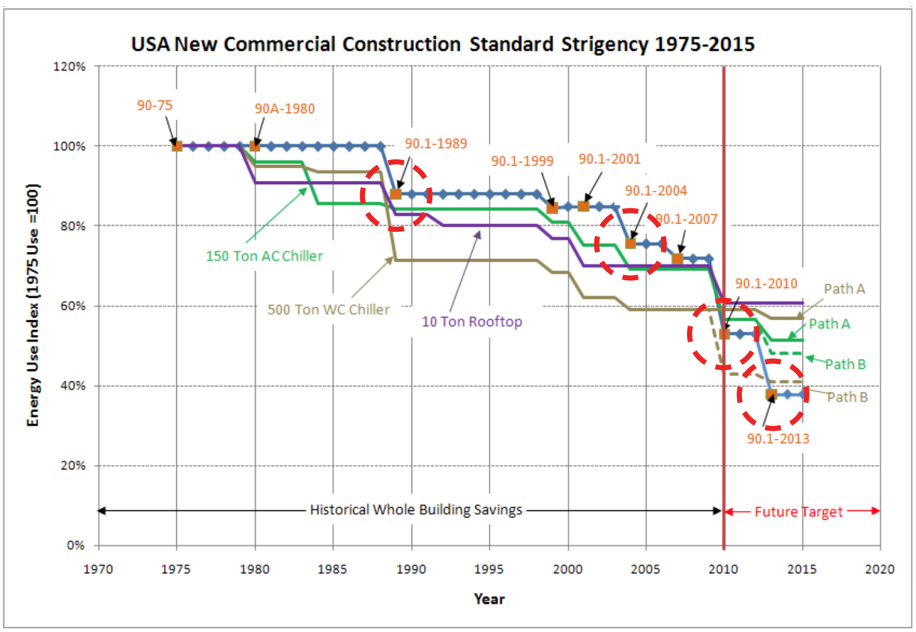


Figure 03: Historical Energy Efficiency Improvements of Buildings
Source: Complying with Standard 90.1-2013: hvac/mechanical

The development of environmental assessment tools and high-performance buildings was an effort to reduce building energy consumption and carbon emissions associated with their operation. Tools such as LEED (Leadership in Energy and Environmental Design), the Living Building Challenge, and BREEAM aim at reducing a building's operational energy and carbon emissions in an effort to minimize the negative environmental impact compared to conventional building methods. Their focus is the reduction of energy demand, carbon emissions, water demand and waste generation.

The reduction of operational energy shed a light on the significance of the less accounted for energy of a building's life cycle, which is embodied energy (EE). During the design process, the extraction of natural resources for construction purposes and the production of building materials are energy-intensive processes that result in significant CO_2 emissions. The extraction and production of building materials constitute part of the building's embodied energy, which is defined as the total energy inputs consumed throughout a product's life cycle. Initial EE represents energy used for the

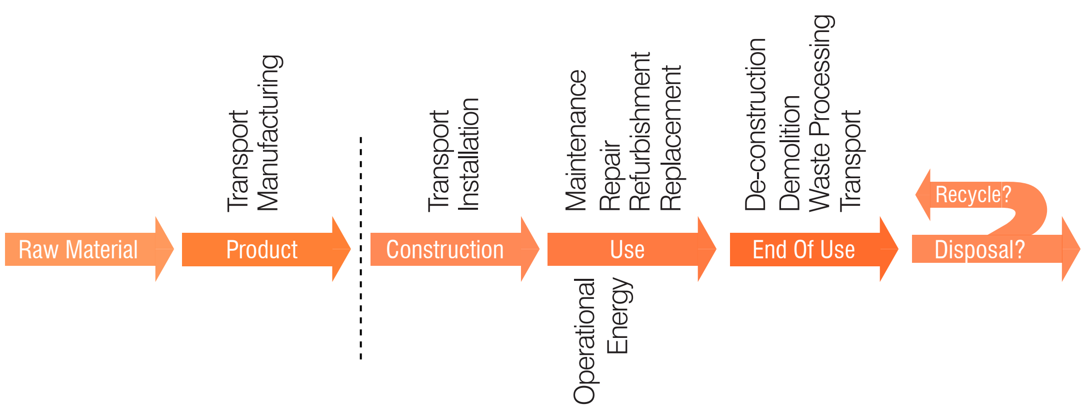


Figure 04: Embodied Energy
Source: Beyer, 2014

extraction of raw materials, transportation to factory, processing and manufacturing, transportation to site, and construction. Once the material is installed, recurring EE represents the energy used to maintain, replace, and recycle materials and components of a building throughout its life.

Embodied energy is a means to quantify the invested energy of a material. It is the basic unit of measure in a life cycle assessment. Natural materials like timber and cut stone tend to be lower in embodied energy because they require fewer manufacturing processes. The more processed materials like metals will generally have higher embodied energy. Manufacturing processes that require high heat require more significant energy compared to processes of cutting and mechanical shaping, including the refinement of metals and the kiln firing of ceramics like brick and terracotta. The EE energy value can begin to translate to carbon dioxide emissions, and when weighed with other factors is measured in a unit called global warming potential. The basic units of embodied energy or global warming potential can vary based on volume, mass or square footage (Moncaster, 2012). Compared with other common building materials such as steel, aluminum and concrete, hardwood timber not only stores carbon it uses up to 85-times less energy in processing. In simple terms, a concrete slab floor uses 60% more energy than a timber floor, double brick walls use almost 5-times more energy than weatherboards on timber framing, and an aluminum window uses 45% more energy than an equivalent timber window. The substitution of timber elements for more

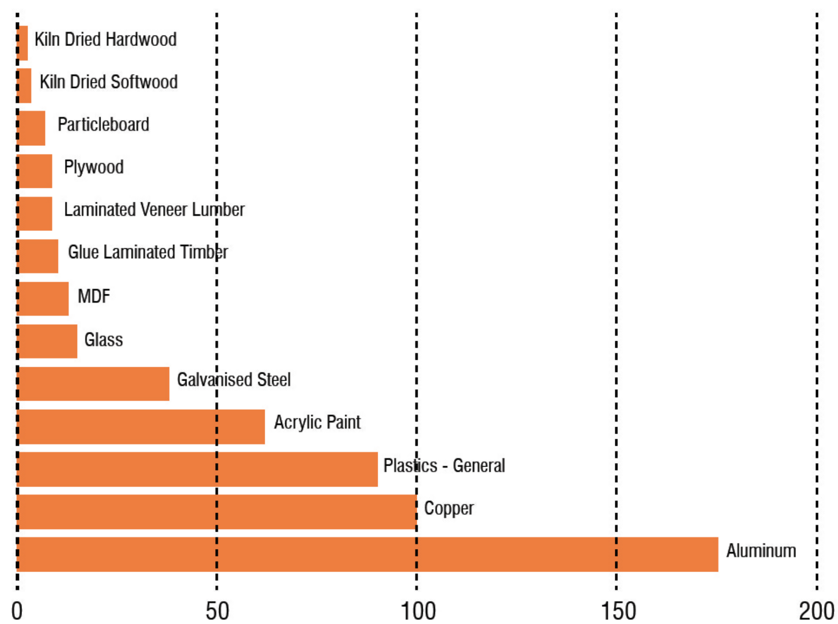


Figure 05: Embodied Energy Values of Various Materials (MJ/kg)
Source: Beyer, 2014

energy intensive products in the building process results in a worthwhile energy saving. Moreover, highly processed timber such as glue-laminated timber, store more carbon within their structure than is released by their manufacture as shown in Figure 05. The following are factors to consider when looking for materials and with low embodied energy:

- The distance needed to transport materials; local sourcing results in lower embodied energy.
- Amount of raw materials used.
- Complexity of manufacturing process. (The more complex the process, the more energy intensive)
- Recycling potential.
- Renewable materials are desirable.
- Efficient building design; where the use of energy and materials is lowered.
- Timber for example is processed from a renewable resource; an actively growing, sustainably managed forest, making it an ideal material choice for environmentally conscious designers and consumers.

1.3 Problem Statement

Variability of EE and CE coefficients, lack of flexibility of available LCA tools, and loyalty to conventional construction methods create a challenge for architects, engineers, and stakeholders in quantifying EE and CE particularly during the design process. The appropriate time to carry out an environmental impact assessment of a building design should at the earliest possible stage, yet the decision is affected by factors such as budget, program and resource availability. In common architectural practice, environmental performance analysis of designs is often left until the design is developed to a detailed stage. The lack of integration of environmental assessments into the design process does not allow for the reduction of the EE and CE that could be avoided.

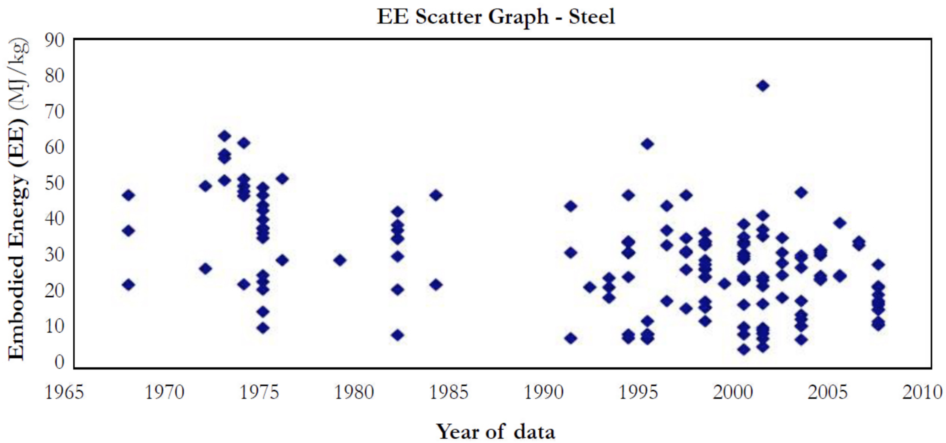


Figure 06: Variability of Available Embodied Energy Data of Steel
Source: Hammond and Jones, 2011

The process of calculating embodied energy and carbon emissions is complex; a variety of data are used from various sources, and factors such as geographical location play a big role on EE due to technology and methods employed in the manufacturing process. An example of the overwhelming variability in available data sources is presented in Figure 06, which indicates the values for embodied energy of structural steel available in the literature over a period of 40 years. Despite this variability, current embodied energy and carbon emission databases are created based on data collected from these unreliable sources. Although efforts are made to ensure the accuracy of the information contained in the University of Bath's inventory of carbon and energy database for example, they are based on public domain sources including journal articles, Life Cycle Assessments, books, and conference papers. Therefore, the energy and carbon data are the "best" coefficients, with no guarantee to the level of accuracy. Moreover, a significant measure that is often estimated or unaccounted for is the transportation energy. Considering the aforementioned challenges, it is critical to review challenges arising from the existing literature on the assessment of embodied energy and carbon emissions of building materials, and find opportunities for the accurately assessment of embodied energy as part of the whole energy life cycle of buildings.

1.4 Significance

As previously mentioned, when high-performance buildings approach net-zero energy demand and carbon neutral operation, the embodied energy and CO_2 emissions due to building construction become a much more significant part of the total energy of a building's life cycle and CO_2 emissions costs (Figure 07). Although less accounted for during the design process, the extraction of natural resources for construction and the production of building materials are energy-intensive processes that release significant CO_2 emissions. Operational energy can be reduced through building performance optimization, whereas embodied energy can only be reduced if low energy intensive materials and products are selected at the initial stages of the design process. Moreover, the lack of information needed for embodied energy assessment and the loyalty of key

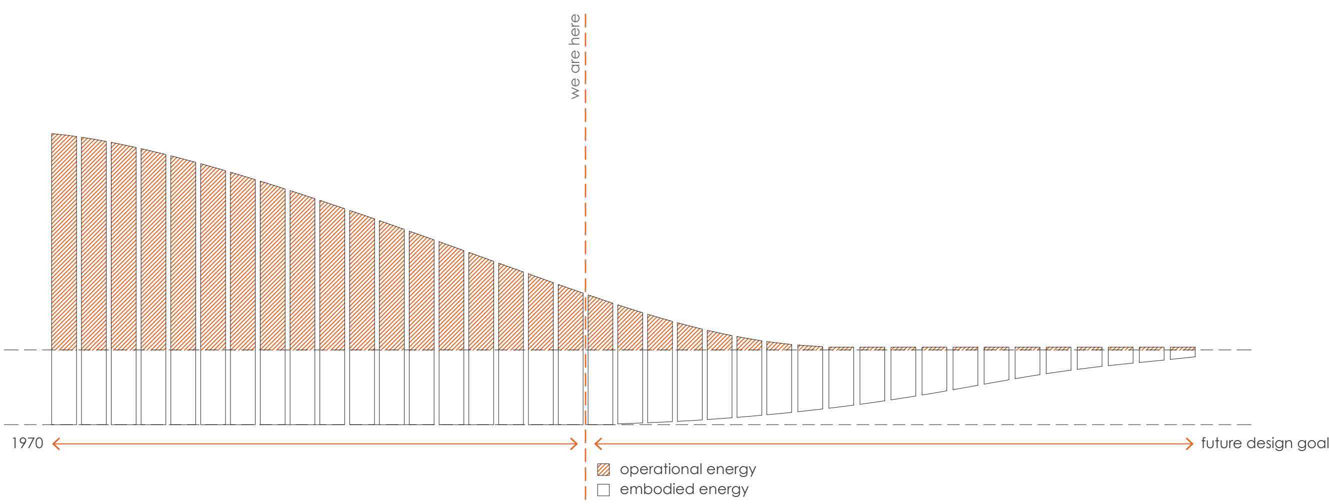


Figure 07: Future Building Life-cycle Energy Design Goal
Source: By Author

players in the design process to conventional construction methods, make the assessment of EE of buildings difficult. Furthermore, the process of calculating embodied energy is complex; a variety of data is used from various sources, and factors such as geographical location play a big role on the EE due to technology and methods employed in the manufacturing process. This research aims

at defining the environmental impacts due to building material selection, through the quantification of material embodied energy and carbon dioxide emissions of a high-performance building. The case study approach limited to the assessment of the embodied energy and carbon emissions of the structural materials and photovoltaic system of a high-performance building facilitated a detailed calculation of the selected materials environmental costs, guarantying a high level of accuracy in comparison with publicly available databases.

1.5 Research Questions

1. How is the environmental impact of building materials assessed and reduced during the architectural design process?
2. How can architecture practice ethos influence the reduction of the environmental impacts of structural building materials ?
3. How does construction embodied energy and CO_2 emissions compare with operational embodied energy and CO_2 emissions over an expected 100-year life of the building?
4. How can the embodied energy assessment be integrated into the building design process?

1.6 Limitations

This study quantifies the reduction of embodied energy and carbon dioxide emissions of the structural system of the Aldo Leopold Legacy Center, located in Baraboo, Wisconsin. It identifies design decisions made throughout the design process, and their associated environmental savings. It provides a detailed analysis of the reduction of embodied energy and carbon dioxide emissions of structural systems due these design decisions, including local sourcing and processing of materials. Material quantities are calculated based on LEED documentation, the Aldo Leopold

Foundation's BIM model and the building's construction documents; all of which can contribute to a small percentage of inaccuracy. Additionally, some materials' manufacturing embodied energy values were taken from the Inventory of Carbon and Emissions (ICE). Additionally, the scope of the research did not include the construction phase or end of life phase energy. The study evaluates the initial embodied energy of material production, its transportation to the site, and the occupancy/use phase energy consumption (Figure 08).

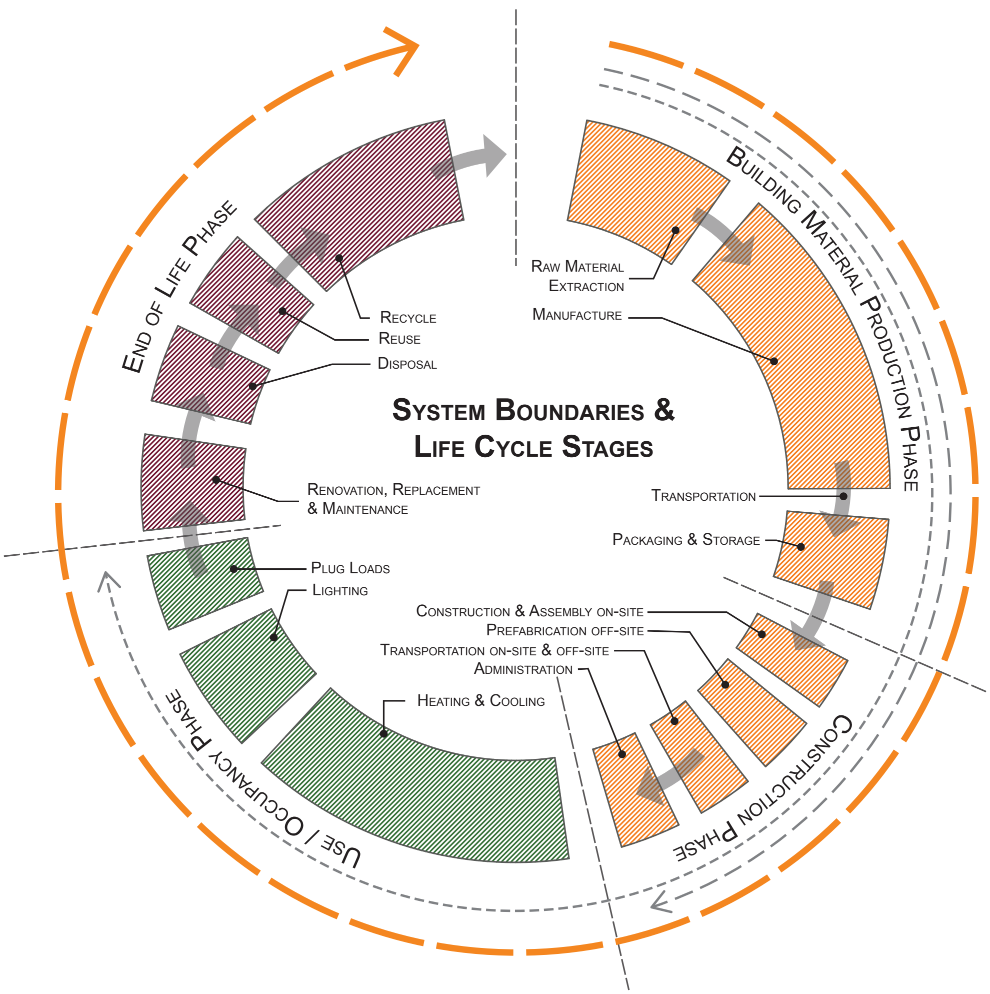


Figure 08: System Boundaries & Life Cycle Stages
Source: By Author

1.7 Key Definitions

- **Embodied Energy:** the total energy inputs consumed throughout a material's lifecycle. Initial embodied energy represents energy used for the extraction of raw materials, processing and manufacturing, transportation, and construction.
- **Embodied CO_2 Emissions:** a measure of the carbon emitted in the atmosphere in the extraction of raw materials, manufacture, and transportation. Additional measures include emissions from construction activity, such as equipment use, transportation of workers to and from the job site, and land disturbance in construction (which causes loss of carbon stored in healthy soils).
- **Initial Embodied Energy:** represents the non-renewable energy consumed in the acquisition of raw materials, their processing, manufacturing, transportation to site, and construction" (Canadian Architect). The Initial Embodied Energy can be subdivided into two parts; direct and indirect energy.
- **Recurring Embodied Energy:** the sum of the energy embodied in the material used in the rehabilitation and maintenance phases.
- **Direct Energy:** the energy used to transport building products to the site and then construct the building.
- **Indirect Energy:** the energy used to acquire, process, and manufacture the building materials, including any transportation related to these activities.
- **Operational Energy:** the amount of energy that is consumed by a building to satisfy the demand for heating, cooling, ventilation, lighting, equipment, and appliances.
- **Operational CO_2 Emissions:** the amount of CO_2 emissions associated with heating, cooling, ventilation, lighting, equipment, and appliances.
- **Life-Cycle Assessment (LCA):** is the compiling and evaluation of the input and outputs and the potential environmental impacts of a product system during its lifetime. (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling).

- **Building Life-Cycle:** refers to the view of a building over the course of its entire life taking into account the design, construction, operation, demolition and waste treatment.
- **High-performance building:** a building that integrates and optimizes all major high-performance building attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity.
- **Net Zero Energy Building:** is a building with zero net energy consumption, meaning the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site.
- **Carbon Neutral Design:** refers to achieving net zero carbon emissions by balancing a measured amount of carbon released with an equivalent amount sequestered or offset.
- **Inventory of Carbon and Energy (ICE):** the University of Bath's embodied energy and embodied carbon database; an inventory of embodied energy and carbon coefficients for building materials.
- **Energy Unit Intensity (EUI):** a building's energy use as a function of its size or other characteristics. EUI is expressed as energy per square foot per year, and is calculated by dividing the total energy consumed by the building in one year (measured in kBtu or GJ) by the total gross floor area of the building.
- **Sustainable Forest Management:** the management of forests according to the principles of sustainable development. Sustainable forest management uses very broad social, economic and environmental goals.
- **Forestry Stewardship Council (FSC)**: an organization established in 1993 to promote responsible management of the world's forests. Its main tools for achieving this are standard setting, certification and labeling of forest products.
- **Global Warming Potential (GWP)**: a relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO_2e which has a GWP of 1.
- **Recycled Content:** the portion of a product that contains materials that have been recovered

or otherwise diverted from the solid waste stream.

- **Sequestration:** accumulation and storage of atmospheric carbon by some building materials (e.g. timber, concrete).

1.8 List of Acronyms

AIA	American Institute of Architects
ALF	Aldo Leopold Foundation
ALLC	Aldo Leopold Legacy Center
ASHRAE	American Society of Heating, Refrigerating, & Air Conditioning Engineers
BIM	Building Information Modeling
CE	Carbon Emissions
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
EE	Embodied Energy
EPA	Environment Protection Agency
EUI	Energy Unit Intensity
FSC	Forestry Stewardship Council
GHGs	Greenhouse Gases
GWP	Global Warming Potential
HVAC	Heating, Ventilation & Air-Conditioning
ICE	Inventory of Carbon and Energy
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
MJ	Mega-Joule
OE	Operational Energy
PV	Photovoltaic
TKWA	The Kubala Washatko Architects
USGBC	U.S. Green Building Council

2 Literature Review

The Earth holds finite resources including raw materials, minerals, fresh water, and fossil fuels, which are either depleting over time or facing unprecedented devastation in the future (Cairns, 2003; Wackernagel et al., 1999). These resources are collectively referred to as the natural capital (Wackernagel et al., 1999). The exhaustion of these natural resources depends on the current and future rate of anthropogenic consumption. Resource consumption is a transformative process where a resource undergoes physical and chemical changes (e.g. fuel combustion and food digestion). Each consumption process, such as fossil fuel consumption for manufacture and construction, results in outputs such as waste and harmful carbon emissions (Lehmann, 2011). For example, the use of raw materials for construction results in fossil fuel consumption for manufacture and construction waste, producing harmful carbon emissions (Hacker et al., 2008; Malla, 2009; Kofoworola and Gheewala, 2009). Increased resource consumption means more waste, discharge, and emission to land, water, and air (Lehmann, 2011; Bruce, 2012).

Our ecosystem has an inherent capacity called the biocapacity to manage resource depletion and the resulting waste, discharge, and emission (Wackernagel et al., 1999). It replenishes resource consumption by processing waste through a series of natural cycles. The balance that existed between the rate of consumption and replenishment has been disturbed (Wackernagel et al., 1999; Holdren and Eherlich, 1974). The rate of consumption has currently surpassed the rate of replenishment (Wackernagel et al., 1999; Bruce, 2012).

2.1 Significance of Embodied Energy

The construction industry contributes significantly to global resource consumption and CO_2 emissions; 40% of renewable and non-renewable resources and 16% of global water are

consumed annually (Palit, 2004; Horvath, 2004; Holtzhausen, 2007; Dixit et al., 2010). Moreover, 60% of global waste is produced from this sector. About two-fifths of the global raw stone, sand and gravel supply, and one-fourth of world's total virgin wood supply is consumed annually (Ding, 2004; Langston and Langston, 2008; Dixit et al., 2010). In the United States, the use of construction materials such as steel and cement between 1975 and 2003 increased by 108% and 57%, respectively (USGS, 2013). A study by the United States Geological Survey (USGS) revealed that the use of total raw materials reported in 2006 was over 26 times the consumption reported in 1900 (Matos, 2009). Figure 09 illustrates the rise in raw material consumption in the United States in the last 106 years. Interestingly, the periods where raw material use declined coincided with events of adverse economic impacts such as a war, energy crisis, or economic recession.

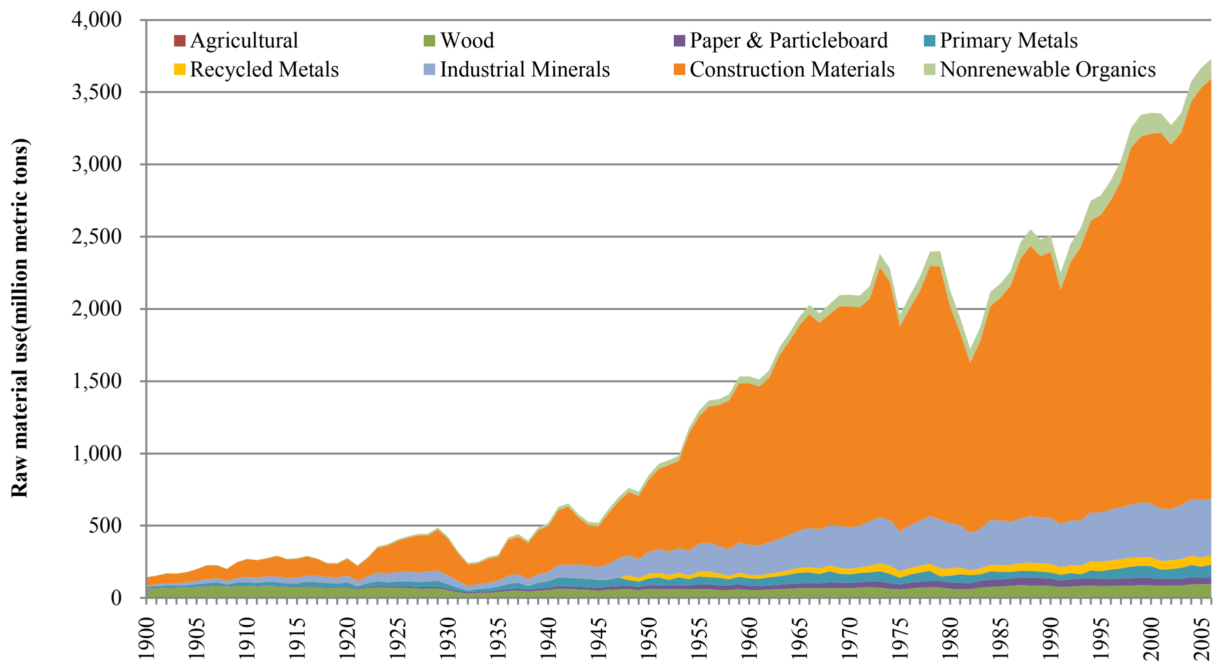


Figure 09: Total Raw Material Use in the United States by Categories
Source: Matos, 2009

The total energy consumed by a building throughout its service life is known as life cycle energy. It is composed of two primary components: operational and embodied energy (Treloar,

1998; Hegner, 2007). Energy sources such as electricity and natural gas are used in the processes of space conditioning, lighting, and powering building appliances during the use of a building are collectively referred to as operational energy (Crowther, 1999; Hegner, 2007; Dixit et al., 2010). Electricity and fuels are also consumed during the extraction, manufacture, delivery and maintenance of a building's constituent materials. Energy that is embedded in all products and processes used in constructing a building is known as embodied energy. The concept of embodied energy is derived from the field of thermodynamics, initially associated with the development of steam engines (Boustead and Hancock, 1979). The challenge at that time was balancing heat gains and losses for the efficient use of fuels. About two decades ago, energy conservation became a publicly recognized concern in developed countries due to the OPEC oil crisis (IFIAS, 1974). Shortly after, energy conservation became a global issue due to the rapid depletion of non-renewable energy sources (fossil fuel reserves), the potential for an enhanced greenhouse effect and problems managing nuclear sources and waste, (England and Casler, 1995; Janssen, 1998; Östblom,1998).

The term embodied energy (EE) has different meanings based on interpretations by different authors, and its published measurements are found to be unclear. Crowther (1999) defined embodied energy as "the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy that is required to manufacture the materials and components of the buildings." Definition by Trelor et al. (2001), "Embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e. traceable backwards from the finished product to consideration of raw materials)." Another interpretation by Boustead and Hancock (as cited by Langston 2008) is, "Embodied energy is defined as the energy demanded by the construction plus all necessary the

necessary upstream processes for materials such as mining, refining, manufacturing, transportation, erection and the like...” A more comprehensive definition given by Baird (1994), Edwards and Stewart (1994), Howard and Roberts (1995), Lawson (1996), and Cole and Kernan (1996) is, “embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building.” These definitions, summarized in Table 01, are a representation of the different views regarding system boundaries within embodied energy analyses.

Source	Embodied Energy Definition Provided
Crowther (1999)	“The total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings.”
Treloar et al. (2000)	“Embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e. traceable backwards from the finished product to consideration of raw materials).”
Dewick and Miozzo (2002)	“The total amount of energy used in the raw materials and manufacture of a certain quantity of material.”
Sartori and Hestnes (2007)	“The sum of all the energy needed to manufacture a good. It may or may not include feedstock energy. Generally expressed in term of primary energy.”
Li et al. (2007)	“Embodied energy is the total energy embodied in construction materials during extraction, manufacturing, transportation, assembly, maintenance, demolition, and final disposal processes.”
Crawford et al. (2006)	“The embodied energy of an entire building, or a building material or product in a building, comprises of indirect and direct energy. Indirect energy is used to create the inputs of goods and services to the main process, whereas direct energy is the energy used for the main process.”
HUB (2009)	“Embodied energy is the sum total of the energy used in a product from raw material extraction and transport to manufacturing, installation, use, disassembly, recycling and disposal and/or decomposition.”
Crawford et al. (2010)	“Embodied energy accounts for the energy associated with the manufacture of products and materials including those resulting from the manufacture of goods and services used during this process.”
Uzsilaityte and Maitinaitis (2010)	“Embodied energy is the amount of energy consumed to create a product, material or service.”
Ramesh et al. (2010)	“Embodied energy is the energy utilized during manufacturing phase of the building. It is the energy content of all the materials used in the building and technical installations, and energy incurred at the time of erection / construction and renovation of the building.”

Table 01: Definitions of Embodied Energy
Source: Dixit, 2013

The total life cycle energy used by a building includes direct and indirect components of embodied and operating energy. Direct energy is consumed in on-site and off-site operations, such

as extraction and manufacture, construction, and transportation. For example, electricity used to power stonecutters and oil consumed by excavators and other equipment is direct energy. The maintenance and replacement of building components also uses direct energy (Cole, 1996; Ding, 2007; Dixit et al., 2012). Indirect energy on the other hand is consumed during the manufacture of building materials used for renovation, refurbishment and demolition purposes. Both direct and indirect energy use are distributed within three stages of the building life cycle: construction, use, and end-of-life stage. Figure 10 shows the overall building life cycle energy.

Embodied energy is divided into three types based on the phase of the building life cycle:

1. Initial Embodied Energy: is energy used during the production of materials, including the extraction of raw materials, manufacture, and final delivery to the construction site.

2. Recurrent embodied energy: the energy used in maintenance and material replacement processes throughout a building's service life.

3. Demolition energy: is energy used for deconstruction and material disposal.

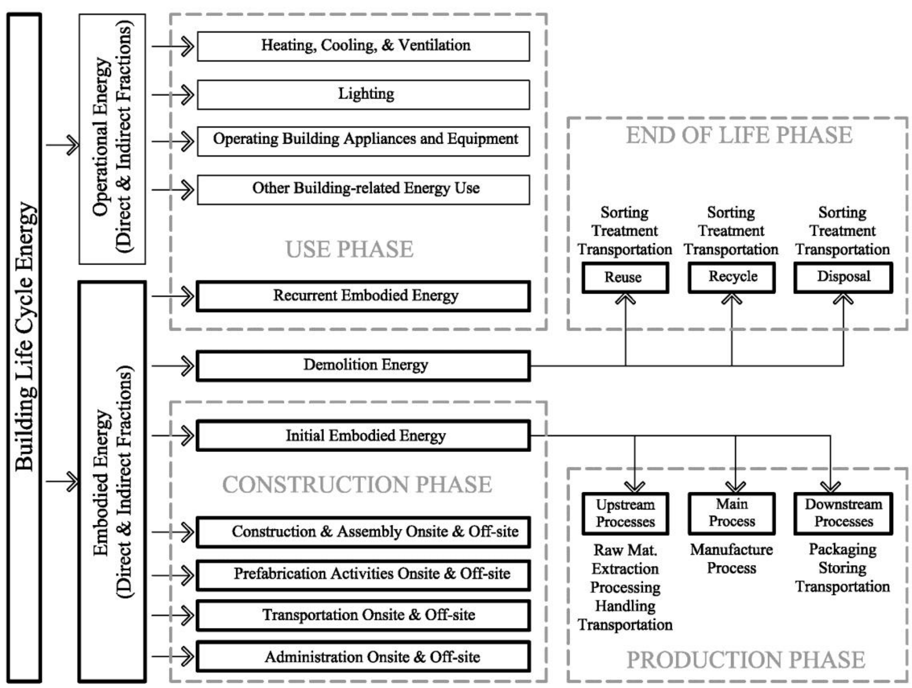


Figure 10: Building Life Cycle Energy
Source: Dixit, 2013

Until recently, energy conservation research focused on the reduction of operational energy of buildings, as it constitutes the largest portion of a building's total life cycle energy. This was accomplished using "Life Cycle Assessment" (LCA) to evaluate the impact of energy consumption used for building construction and operation on the environment. Although this assessment includes the extraction and processing of raw materials; manufacturing, transportation, use and disposal, its major goal is to determine the overall impact of buildings. With the emergence of energy efficient buildings that have low operational energy, current research is placing more emphasis on the significance of embodied energy and its relative proportion of total building energy. Sartori and Hestnes (2007) reviewed 60 case studies in the literature, and found that for a conventional building, the embodied energy can account for 2-38% of the total life cycle energy, whereas for a low energy (high-performance) building, the embodied energy increases to 9-46% of the total life cycle energy. Moreover, in net-zero energy buildings where energy consumption is zero, (the total amount of energy used by the building is roughly equal to the amount of renewable energy created on the site), embodied energy accounts for 100% of the total life cycle energy of a building. Holtzhausen (2007) suggested that ignoring the significance of embodied energy when undertaking a Life Cycle Assessment can be environmentally costly due to the exhaustion of resources and the associated harmful emissions.

2.2 Challenges in EE Assessment

Embodied energy values for building materials vary considerably across published research with a discrepancy ranging between 30 - 40% (Pears, 1996). Pullen (2000) argues that the inconsistency in available embodied energy values can be attributed to the exclusion of upstream processes (raw materials extraction and transportation) and downstream processes (transportation

of materials to the construction site). Several authors [Buchanan and Honey (1994), Crowther (1999), Crawford and Trelor (2003), Ding (2004), and Langston and Langston (2008)] suggested that information obtained from different sources, and on which they based their analysis, was the cause for the significant variation in results. These variations complicate efforts to compare embodied energy values for different building materials (Khasreen et al., 2009). Environmentally conscious decision-making by building professionals for the selection of low embodied energy building material cannot rely on inconsistent, incomplete, and inaccurate data (Fernandez, 2006; Burnett, 2006). Table 02 shows the variations in embodied energy values of commonly used

	Embodied Energy in MJ/kg of Building Material													
	Virgin Steel	Primary Aluminum	Cement	Glass	PVC	Fiberglass Ins.	Gypsum/Plasterboard	Bricks	Concrete	Plywood	Timber	Aggregates	Cellulose Ins.	Polystyrene, Exp.
Honey & Buchanan (1992)	34.9	129.5	8.9	31.5	96.0	23.0			3.1	18.9	1.7	0.3		100.0
Kernan (1996)	28.0	274.0		18.7			9.8	2.5	0.8		9.9	0.3		105.0
Adalberth (1997a)	32.0			26.0	88.7		8.6		2.0		5.2			106.7
Blanchard & Reppe (1998)	37.3	207.8		18.4	77.4	24.5	3.8	4.5	1.6	8.3	5.8	0.9	3.2	100.3
Eaton Et al. (1998)	25.5	200.0					2.7	5.8	0.8		13.0			
Chen et al. (2001)	32.0	191.0	7.8	16.1	70.0	30.3	8.6	2.5	1.0	18.9	5.2	0.1	3.3	105.0
Alcorn (2003)	31.3	192.0	6.2	15.9	60.9	32.1	7.4	2.7	0.9	11.9	2.8	0.4	4.3	58.4
Scheuer et al. (2003)	30.6	207.0	3.7	6.8	60.7	17.6	0.9	2.7			10.8	0.2		94.4
Reddy (2004)	42.0	236.8	4.2					1.4						
Almeida et al. (2005)	10.1	160.2		18.4			4.0		1.1		0.7			100.4
Yohanis & Norton (2006)	42.0	236.8	5.9	25.8										
Pullen (2007)	55.5	378.5	6.6	83.6	121.5		13.3	5.4	2.4	11.9	22.6	1.7		
Crawford (2004)	97.5	259.1	14.5		141.8									
Huberman & Pearlmutter (2008)	35.0	211.0		18.0					1.2					116.0
Hammond & Jones (2008)	35.3		4.6	15.0					1.0	15.0	8.5			
Hammond and Jones (2011)	31.3	218.0	5.2	15.0	70.6	28.0	3.5	3.0	2.9	13.6	7.1	0.1	3.3	100.1
Ramesh et al. (2013)	28.2	236.8	6.7	25.8	158.0									

Table 02: Embodied Energy of Commonly Used Building Materials Reported in Literature
Source: Dixit, 2013

building materials in the literature. Dixit (2010) points to parameters related to embodied energy calculation methods that cause embodied energy values to differ across research studies. These parameters fall into two categories: methodological parameters and data quality parameters. Methodological parameters include system boundary, methods of embodied energy assessment, and the energy inputs included in the embodied energy evaluation process.

2.2.1 System Boundary:

The system boundary defines a system of processes related to the manufacture of a material and determines the type of energy and material inputs included in the calculation (IFIAS, 1975; Peuportier, 2001). Suh et al. (2004) stated that some studies select the system boundary of the embodied energy assessment subjectively resulting in incomparable studies. Miller (2001) and Khasreen et al. (2009) found that research studies do not clearly define the system boundary adopted in their research making it difficult to determine what was included and excluded from the embodied energy calculation. The system boundary demarcations vary across studies, which leads to variations in the calculated embodied energy values (Dixit et al., 2010). Reynolds et al. (2000) emphasized the need for a comprehensive system to ensure reliable system boundary selection.

2.2.2 Embodied Energy Calculation Methods:

Typical embodied energy calculation methods are input-output-based, process-based, a hybrid of both, and statistical analyses (Fay and Treloar, 1998; Lenzen, 2000). Each of these methods has limitations and varying levels of accuracy. The hybrid method includes both process-based and input-output data based methods making it the most comprehensive. Nassen et al. (2007) implemented a detailed analysis using input-output and process-based energy calculation methods and found that the input-output-based analysis results could be 90% higher than a process-based analysis. Crawford and Treloar (2003) calculated embodied energy in a residential and a commercial building with a result of 6.6 GJ/m^2 and 9.0 GJ/m^2 respectively using a process-based analysis method. They found that embodied energy in the studied buildings could decrease by 14.5 - 23% if an input-output-based analysis is used. Crawford and Treloar (2005) later assessed the embodied energy of a commercial building and concluded that when an input-output-based calculation was performed, the result increased by 56% from the building's process-based values. Optis and Wild (2010) concluded that about 78% of published literature fails to provide an accurate description of

the methodology adopted for the embodied energy calculations of building materials.

2.2.2 Energy Inputs:

- *Primary and Delivered Energy:*

"Primary" and "delivered" are the two forms of energy embodied in buildings and materials. Delivered energy is the energy used by consumers such as electricity, it is also known as "end use," "site," or, "final" energy (Dixit, 2013). Primary energy is extracted, processed, and converted to a form (delivered energy) that is usable (Dixit et al., 2010). Primary energy differs from delivered energy and is typically of higher value due to factors such as fuel types used and the means of delivered energy production (e.g. coal fired, natural gas fired, nuclear or hydro power plants) (Thormark, 2002; Sartori and Hestnes, 2007). Each power plant has differing efficiency and uses relatively more primary energy to generate delivered energy. For example, Fay et al. (2000) compared primary and delivered energy units, and found that for every single unit of delivered electricity, 3.4 units of primary energy is used in Australia. This 3.4 factor is referred to as the "conversion factor" or "primary energy factor", and varies globally (Sartori and Hestnes, 2007). Embodied energy presented in primary energy terms can portray a true picture of environmental burden, as primary energy values could provide a relatively accurate estimate of resulting greenhouse gas emissions (Pullen, 2007; Fridley et al., 2008; Gustavsson and Joelsson, 2010; Hernandez and Kenny, 2010). Studies calculated energy embodied in buildings and building materials either in a primary or delivered energy term or have not provided indication of the energy term (Sartori and Hestnes, 2007; Gustavsson and Joelsson, 2010; Ramesh et al., 2010). Pears (1996) revealed that embodied energy values could increase by 30 - 40% (from delivered energy term) if reported in a primary energy form.

- *Feedstock Energy:*

Feedstock energy is energy used in the manufacture process of a material. ISO 14040

(2006) defined feedstock energy as “heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value.” Petrochemicals such as oil and gas for example, are used as material inputs in the manufacture process of materials such as plastics. Research studies have concluded that the feedstock energy could constitute a major fraction of the total embodied energy. Sartori and Hestnes (2007) argued that the embodied energy may or may not include the feedstock energy. However, research done by Thormark (2002 and 2006), Lucuik et al. (2006), Trusty (2006), Ardente et al. (2008), Blengini (2009) and Gustavsson et al. (2010) accommodated feedstock energy into the total embodied energy calculations. Some of these studies (Thormark, 2002; Trusty, 2006; Thormark, 2007; Ardente et al., 2008) presented the values of feedstock energy separately to highlight their importance. Thormark (2001) and (2007) found the feedstock energy as 27 - 94% of the materials’ embodied energy. Ardente et al. (2008) completed a “cradle to gate” LCA of Kenaf-fiber insulation boards and found that nearly 50% of the total embodied energy was attributed to the feedstock energy of the material.

A similar study conducted by Lazzarin et al. (2008) quantified the feedstock energy of stone wool, expanded polystyrene foam, expanded polyurethane foam, and cork panels as 16%, 48%, 59%, and 88% of the material’s total embodied energy, respectively. The feedstock component is the largest contributor to the total energy embodied in construction materials such as asphalt (Trusty, 2006). Feedstock energy, therefore, is significant and should be included in embodied energy assessments (Thormark, 2006; Nassen et al., 2007; Ardente et al., 2008; Hammond and Jones, 2008 and 2010). Nassen et al. (2007) notes that assessment methods often do not take into account feedstock energy of raw material inputs. However, inclusion or exclusion of feedstock energy in embodied energy calculation causes variations in embodied energy values (Pullen, 2000b; Nassen et al., 2007).

- *Human Energy:*

In some geographic locations, conventional manufacturing processes of building materials and construction processes are labor-intensive requiring a considerable amount of human energy (Huberman and Pearlmutter, 2008). Langston and Langston (2007) noted that a portion of a building's life cycle activities such as maintenance and repair are more labor intensive compared to initial construction, and this fraction of human energy is often excluded from the embodied energy analysis. Several studies have emphasized the need to include human energy in embodied energy analysis (Langston and Langston, 2007; Pulselli et al., 2009). However, this energy source is often excluded in embodied energy assessment because of our inability to accurately calculate the human energy contribution. Dias and Pooliyadda (2004) discussed the importance of human energy but were unable to accommodate it in their calculations due to the complexity and ambiguity of the analysis process.

A significant study that calculated human energy was done by Alshboul and Alzoubi (2008) who assessed embodied energy of the natural-dimensioned stone in Jordan. They measured human energy using work duration and metabolic rates and found that the variability of individual metabolic rates poses difficulty in consistently calculating human energy. Another important work by Cleveland and Costanza (2008) discussed human labor and identified three components, which need to be accounted for while quantifying the human energy; the calorific value of food consumption of workers, food embodied energy, and fuel consumed for worker's transportation. Current embodied energy methods fail to include the human energy component of total embodied energy (Langston and Langston, 2007; Ulgiati et al., 2010). Grondzik et al. (2009) noted that some building materials are more human energy intensive than others that consume more mechanical energy. This further adds to the variability of materials' embodied energy values.

Calculations by different organizations cannot be compared because not all include

the same energy inputs. Some analysts include the energy used to transport building materials and construction workers to the building site, while others omit these inputs. Some include the energy used to make the machines and to build the factories that are used to manufacture building materials, while others omit these inputs. Moreover, published data are often out of date. In her 1995 Home Energy article "Reducing the Embodied Energy of Buildings", Tracy Mumma wrote, "Part of the challenge of assessing and making decisions based on embodied energy is the lack of current data. The definitive U.S. study on embodied energy was produced under the auspices of the Energy Research and Development Administration and dates from December 1976. Many of the statistics it includes are of 1967 vintage, and most current papers and references on embodied energy still cite data drawn from this old study. While some of the data may still be relevant, the tremendous advances in processing technology and recycling during the past 20 years limit the applicability of this information. Tools, transportation, and installation methods have changed, and most significantly, some building materials in widespread use today didn't even exist at the time the report came out."

Due to the complexity of calculations and the wide range of production methods, transportation distances and other variables for some building products, exact figures for embodied energy vary from one study to another. The quantification of embodied energy for any particular material is an inexact science, requiring a long view look at the entire manufacturing and utilization process, and filled with a large number of potentially significant variables. Consequently, the complexity of embodied energy calculations is frustrating even for researchers, and it is easy for the individual homeowner, builder, designer or government specifier to become discouraged at the difficulty of obtaining accurate figures (Mumma, 1995). The process of calculating embodied energy and carbon emissions is complex; a variety of data is used from various sources, and factors such as geographical location play a big role on embodied energy due to technology and methods

employed in the manufacturing process.

Despite the overwhelming variability in data sources, available material databases are based on data collected from these sources. The University of Bath's Inventory of Carbon and Energy (ICE) is a comprehensive database for embodied energy and carbon values associated with building materials. The database was originally populated with materials found in the CIBSE (Chartered Institution of Building Services Engineers) guide, with initial embodied energy values extracted from Boustead and Hancock's "Handbook of Industrial Energy Analysis". The database provides a means for researchers and practitioners to estimate the embodied energy and carbon in buildings and civil engineering structures. In their paper, Hammond & Jones (2008a) disclose that values of EE and CE are not precise when applied to a general category of material (aluminum, steel or timber). However, they can be considered good benchmarks for use in determining the life cycle performance of buildings and manufactured products. The boundaries within the ICE database are cradle-to-gate. There are possible variations affecting the absolute boundaries of the study due to the utilization of secondary data resources, which have variable boundaries that can be responsible for large differences in results (Hammond & Jones, 2011).

To sum up, the literature suggests that the assessment of the embodied energy is difficult, and there is currently no standard methodology to estimate the embodied energy of building materials. Parameters influencing the embodied energy assessment indicated in the literature review are:

1. Systems Boundaries

Boundary definition is critical in that it could be responsible for the exclusion of upstream processes that cause significant difference in embodied energy calculations results.

2. Embodied Energy Analysis Methods

The three main analysis processes of embodied energy are process-based, input-output

based, and hybrid-based (Ding, 2004; Lenzen, 2006). The results from these methods vary due to inherent limitations on each.

3. Primary and Secondary Energy

Research studies have calculated energy embodied in buildings and building materials either in a primary or delivered energy term, or have not provided indication of the energy term (Sartori and Hestnes, 2007; Gustavsson and Joelsson, 2010; Ramesh et al., 2010). Pears (1996) found that embodied energy values could increase by 30 - 40% if reported in a primary energy form compared to delivered energy.

4. Data Source

Researchers use a subjective approach to obtain embodied energy values. While some researchers derive their own embodied energy values, others rely on publicly available energy databases. This subjective selection influences the study results significantly (Ding, 2004). The majority of published embodied energy coefficients are derived from a single source of information that is questioned regarding the accuracy and reliability of the data source (Pears, 1996). The source of data used for embodied energy assessments is an important parameter, and its reliability, uncertainty, and transparency must be considered while performing energy life cycle assessments (Pullen, 2006).

5. Technology of Manufacturing Processes

Although in the same time frame and geographic location, using different technologies for the extraction and manufacture of materials results in dissimilarity of energy consumption values. Different production technologies and types of energy in the process could be responsible for significant differences in embodied energy values (Pears, 1996).Technological processes should be considered in embodied energy assessment to eliminate inconsistency and variability in results (Menzies, 2007; Peerebom, 1998).

6. Comprehensiveness of Data

Menzies et al. (2007) and Peereboom et al. (1998) argue that researchers often do not have access to primary data sources, therefore rely on incomplete secondary sources. These referenced data sources are incomplete because they either used an improper method of calculation or subjectively selected system boundaries. Menzies et al. (2007) suggest that accessibility of data, methodology adopted, and selection of system boundaries govern the completeness of data that eventually affects the reliability of results. According to Alcorn and Wood (1998), comprehensiveness of data is a vital quality that should be considered when selecting one material dataset over another.

7. Geographic Location of Study Area

Countries differ from each other in raw material characteristics, production processes, economic data, processes of delivered energy generation, transportation distances, fuel fin transportation, and labor. These differences affect the end results of embodied energy assessments causing significant variations (Ding, 2004; Lenzen, 2006).

8. Age of Data Sources

The age of data sources used in life cycle assessment (LCA) studies is critical. It can have significant influence on the comparability of the energy if derived from obsolete manufacturing technologies that are not as energy efficient as newer technologies for example. Moreover, relying on old transportation energy data affects energy values; newer vehicles are more fuel-efficient and might use different fuel types. Studies based on such flawed data sources are inaccurate and misleading (Peerebom, 1998).

9. Feedstock Energy

Research studies have concluded that the feedstock energy could constitute a major fraction of the total embodied energy. The feedstock parameter is the largest contributor to the total energy embodied in construction materials such as asphalt for example (Trusty, 2006). Nassen et al. (2007) states that assessment methods often do not account feedstock energy of raw material inputs. However, inclusion or exclusion of feedstock energy in embodied energy calculation causes variations in embodied energy values (Pullen, 2000b; Nassen et al., 2007).

2.3 Embodied Energy Assessment Strategies

This section will discuss the improvement in the evaluation process of embodied energy of materials in terms of to two main issues. The first is related to system boundary, while the second is associated with the existing embodied energy calculation methods.

2.3.1 System Boundary Definitions in Literature

A system boundary demarcates the structure of various products and processes used in the manufacturing of a material. It also determines the number and type of energy inputs, and waste and emission outputs included in the embodied energy calculation (Peuportier, 2001; IFIAS, 1975). A system boundary for a material begins anywhere from raw material extraction and manufacture, to demolition and disposal. System boundaries for buildings include “cradle to gate,” “cradle to site,” and “cradle to grave.” The cradle to gate system boundary includes upstream processes from raw material extraction till the finished product leaves the factory gate, excluding transport of material to the building site (Frey, 2008, Goggins et al., 2010). The cradle to site system boundary includes cradle to gate and transportation of finished product to the construction site, on-site construction and assembly processes, wastage disposal, etc. (Hammond and Jones, 2008). The cradle to grave system boundary takes into account building operations, maintenance, renovation,

refurbishment, and retrofit activities. The end-of-life phase includes processes such as building demolition, waste sorting and hauling, recycling and reuse, and waste disposal to landfills is also included (Hammond and Jones, 2010). The cradle to grave boundary provides a complete life cycle analysis, which is critical for an accurate ecological cost assessment (Plank, 2008; Hammond and Jones, 2010; Khasreen et al., 2009; Vukotic et al., 2010). Figure 11 illustrates the aforementioned system boundary discussed in the literature.

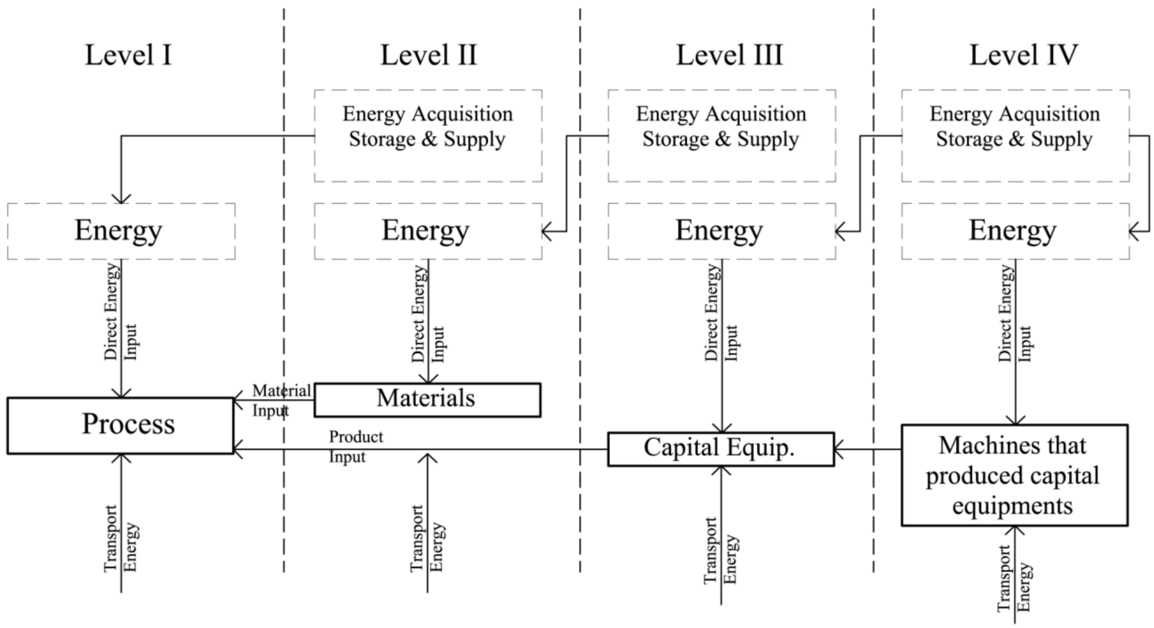


Figure 11: Proposed System Boundary Model
Source: IFIAS (The International Federation of Institutes of Advanced Studies), 1975

Buchanan and Honey (1994) and Hammond and Jones (2010) explained four levels of system boundary regression. The first level included direct energy inputs of a building's life cycle such as construction, prefabrication, maintenance, replacement, demolition, and disposal. Energy embodied in the production, upstream and downstream processes of building materials were included in the second level of regression. Hammond and Jones (2010) found that approximately 90% of the energy inputs could be tracked and determined through a second level of regression. The assessment of inputs beyond this level requires more time and effort, therefore studies with

analyses beyond the second level are limited (Hammond & Jones, 2010). A third regression level covers the energy consumed in production, delivery, and installation of machines consumed in the manufacturing of building materials, and on-site and off-site construction processes. The fourth regression level is the most difficult to calculate, and includes manufacturing energy consumed in the production of machines used in the third level regression (Hammond & Jones, 2010). Figure 12 illustrates the four regression levels of a system boundary model for embodied energy assessment.

Atkinson (1996) proposed tracking energy inputs of a building from its manufacture both upstream and downstream to the biosphere as shown in Figure 12. Each phase of the building's life cycle involved the output of solid, liquid, or gaseous waste and emissions impacting the ecosystem

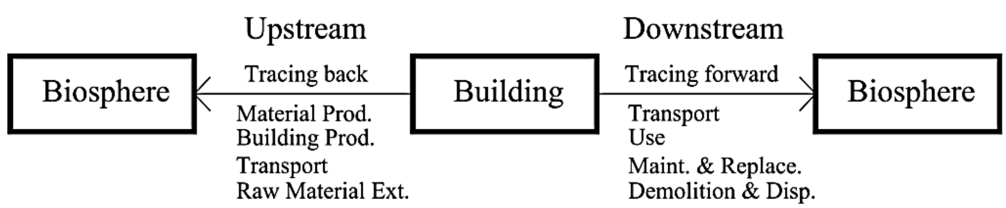


Figure 12: Simplified System Boundary Model Proposed by Atkinson
Source: Atkinson, 1996

(Atkinson, 1996). Edwards and Bennett (2003) proposed a product system (Figure 13), which covered water, primary and delivered energy inputs, and their acquisition in the upstream. Resulting

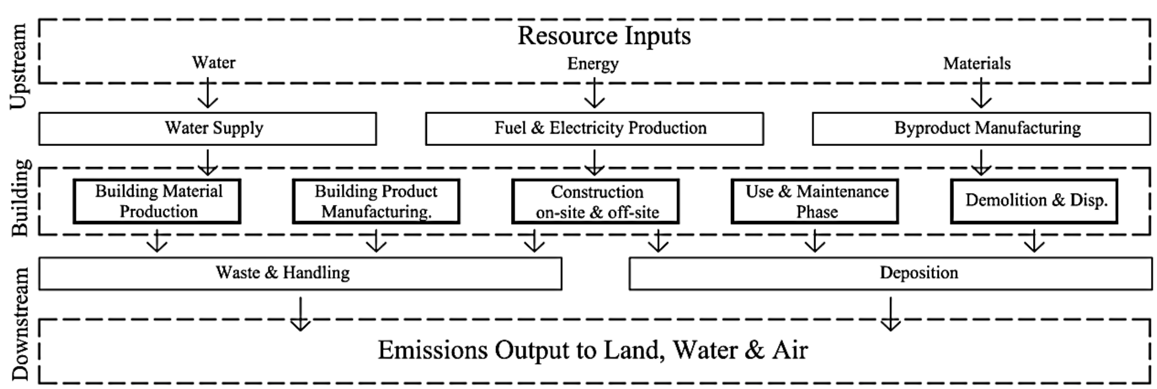


Figure 13: System Boundary Proposed by Edwards and Bennett
Source: Edwards and Bennett, 2003

waste and emissions are included in the downstream. Similarly, Ries and Mahdavi (2001) defined a system boundary that incorporated land use in addition to the energy embodied in the capital infrastructure. A multi-dimensional model comprised of five levels was proposed by Murphy et al. (2011). Figure 14 illustrates Murphy's system boundary, which encompasses direct and indirect energy inputs, human labor, supportive and environmental inputs. An "extended system boundary" was another definition suggested by Kua and Wong (2012), which added the impacts of managing waste produced during a building's operation to the system boundary.

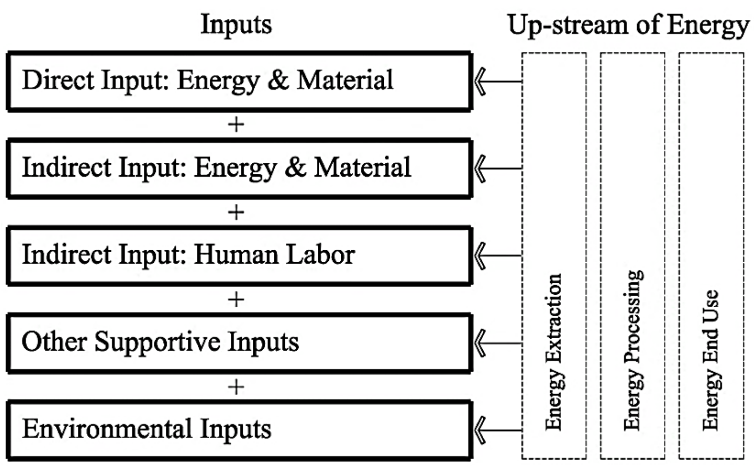


Figure 14: System Boundary Model Proposed by Murphy et al.
Source: Murphy et al., 2011

The aforementioned proposed system boundaries differed in three ways. First, research studies included one or a selection of life cycle stages for the embodied energy assessment of buildings (Edwards et al., 1994; Ding, 2004). Second, it is unclear as to the extent of the upstream and downstream processes of each life cycle stage (Horvath, 2004; Weidema et al., 2008; Heijungs et al., 2009). Finally, the consideration of the embodied energy calculation of the whole building was limited; studies covered one or more building components such as building structure, envelope, finishes, services (Ding, 2004; Edwards et al., 1994; Optis and Wild, 2010). These differences in boundary definition caused variation in embodied energy values due to the exclusion of important

life cycle stages or building components (Ding, 2004; Khasreen et al., 2009). Literature including (Hegner, 2007; Krogmann et al., 2008) for example, pointed out obstacles such as the inclusion of human energy, capital energy, feedstock energy, and renewable energy. Only few studies (e.g., Cole, 1999; Vukotic et al., 2010) incorporated processes such as transportation for materials, equipment, and labor, while others were limited to the transportation of materials. Raynolds et al. (2000) emphasized a need for a system that ensures consistent system boundary selection across different studies.

2.3.2 Embodied Energy Assessment Methods

Process-based analysis is the most widely used method of embodied energy assessment, as it delivers more accurate (Ding, 2004) and reliable results (Alcorn and Baird, 1996; Pullen, 2000b; Crawford and Treloar, 2003). The process begins with the building material as a final product and works backward in the upstream of the main process. This process takes into account most direct and indirect energy inputs embodied in each constituent of a material (Treloar, 1998; Alcorn and Baird, 1996). It is difficult however to track most indirect energy inputs. For example, embodied energy in concrete can be calculated if the embodied energy of cement is identified. Similarly the embodied energy of cement can be determined if the data about energy contents of clinker are available. In the upstream process of concrete, most of the indirect energy inputs can be tracked. However, after a certain point in the upstream process, tracking energy inputs is truncated. This truncation is due to both the lack of data (Treloar, 1998; Crawford, 2004; Acquaye, 2010) and the extensive effort needed to identify and quantify each material and energy input to the complex upstream processes (Alcorn and Baird, 1996; Treloar et al., 2001b; Ding, 2004; Crawford and Treloar, 2005). Process-based embodied energy assessment is both data-intensive and time-consuming, as all energy inputs need to be tracked (Crawford, 2004) . It is an accurate

assessment process, yet incomplete due to truncation of energy input tracking (Dixit et al, 2010). Lenzen (2000) estimated that the incompleteness and error resulting from process analysis to be as high as 50% and 10% respectively.

Pears (1996), Crawford et al. (2002), Ding (2004), and Dixit (2010) conclude that despite the efforts to define a system boundary and achieve a suitable method to calculate the embodied energy of materials, reliable, consistent and accurate embodied energy information is not available. Moreover, embodied energy assessment is not well integrated in design and construction practices, and decisions are still made based on capitol cost.

Recently, a number of leading architecture and structural engineering firms such as Kieran Timberlake and SOM, are developing tools for the estimation of embodied energy and CO_2 emissions of building materials. Continuous efforts to estimate EE indicate the need for a conceptual tool and reliable database for accurate assessment of the ecological cost of building material selection. Despite the availability of a number of methods to compute the embodied energy in building materials, these methods generate differing results. Differing parameters cause significant variation in reported EE figures, leaving the industry with published yet incomparable embodied energy values (Dixit et al 2010). Global comparability and reliability are fundamental data qualities for embodied energy research. Hammond & Jones (2008) reveal the variation in published data can be attributed to differences in boundary definitions (including geographic origin), age of the data sources and accuracy of life cycle assessments. The majority of currently available databases include data derived using guidelines set by International Standardization Organization (ISO) for Life Cycle Assessment (LCA). Research studies performed either energy analysis or LCA to calculate embodied and operational energy in the whole life cycle of a building. Studies (Pullen, 1996; Gustavsson, 2010; Huberman, 2008) that performed LCA used either ISO

LCA standards or none. ISO LCA standards do not provide comprehensive guidance to building life cycle assessment; system boundary definition and data quality remain unresolved (Reap et al, 2008; Zamagni et al, 2008).

The University of Bath's ICE inventory; a comprehensive database for embodied energy and carbon values associated with the construction of materials, was originally populated with materials found in the CIBSE guide, with initial embodied energy values extracted from Boustead and Hancock's "Handbook of Industrial Energy Analysis". The database provides a means for researchers and practitioners to estimate the embodied energy and carbon in buildings and civil engineering structures. In their paper, Hammond and Jones (2008a) disclose that values of EE and CE are not precise when applied to a general category of material (aluminum, steel or timber). However, they can be considered good benchmarks for use in determining the life-cycle performance of buildings and materials. Although efforts are made to ensure the accuracy of the information contained in the inventory, they are based on public domain sources including journal articles, Life Cycle Assessments, books, and conference papers. According to Hammond & Jones (2008a) the energy and carbon data are considered to be the "best" coefficients, with no guarantee to the level of accuracy.

Although efforts are made to ensure the accuracy of the information contained in the inventory, they are based on public domain sources including journal articles, Life Cycle Assessments, books, and conference papers. Therefore, the energy and carbon data are the "best" coefficients, with no guarantee to the level of accuracy. A significant measure that is often estimated or unaccounted for is the transportation energy. Available material embodied energy and carbon emissions data are limited and variable making it unreliable. A number of LCA tools in the form of software are available, including ATHENA, BEES 4.0, Ecoinvent, Eco-Quantum, Envest, OPTIMIZE, LICHEE, SimaPro. Although these tools are user friendly, most of them do

not cover all stages of a building's life cycle. None of the existing tools and datasets possesses the capability of performing a full building life cycle assessment (Khasreen et al, 2009; Miller, 2001). The Waste Reduction Action Program (WRAP) provides a project-based database of embodied carbon, excluding material quantities (UKGBC, 2013). Additionally, the database is only open to UK professionals (450 total users) and is based on the information given by its participants.

Among prevailing environmental practices are eco-labeling, environmental selection of building materials and products and the green building assessment. The eco-labeling of a product is comparatively useful in informing consumers or customers about the product's environmental characteristics (Marin and Tobler, 2002; Trusty, 2004; Levan, 1995; Hes, 2000). The embodied energy of a product is a useful criterion for judging environmental performance (Wan, 2008; Vonka, 2005) and if embodied energy data are inaccurate and possess variations, the purpose of eco-labeling is not fulfilled. Environmental selection of materials or products could result in large savings in energy use and eventual decrease in CO2 emissions due to energy production (Atkinson et al., 1996; Gonzalez and Navarro, 2006; Thormark, 2006). Atkinson et al. (1996) found that energy savings due to environmental preference could be as great as 20%, while Thormark (2006) determined a reduction of 17% and an increase of 6% in embodied energy values due to the right and wrong selection of materials. Unfortunately, no reliable information exists regarding the embodied energy of a material or product, which could be used for the purpose of environmental preference (Fernandez, 2006). Available information on embodied energy is uncertain; thus, people involved in decision-making and their decisions are influenced by uncertainty (Pears, 1996). Differing embodied energy data pose difficulty in making the right decisions about selecting environment friendly materials or products (Pears, 1996; Worth, 1996; Davies, 2001: Ross, 2000).

Literature suggests that a set of reliable standards/benchmarks can minimize problems of variation in energy data, providing accuracy and comprehensiveness to embodied energy values.

Recognizing this need, DeWolf & Ochesndorf, (2014) created an interactive, growing database of building projects allowing architects, engineers and researchers to input data on material quantities and embodied energy impact of their projects. This initiative however, results in embodied energy averages similar to suggested values in other databases, where accuracy of values participants input in a growing database is questionable regardless of the database management validation of accuracy prior to publishing the data. Moreover, rating schemes such as LEED v4 for example, have begun to encompass the environmental cost of embodied energy in their credit system. However, an improvement on an undefined baseline building is required to achieve the credit (USGBC, LEED v4, 2013).

2.4 Research Gaps

Based on the literature review, a consensus on the definition of embodied energy is unclear. This definition is tied to what is included and/or excluded in the embodied energy assessment. A model to define a system boundary comprehensively needs to be developed to provide accurate embodied energy data. Due to their subjective selection, the variability of system boundaries is a primary methodological problem with embodied energy studies. Despite growing effort by researchers such as Treloar (1998), Crawford (2004), and Langston, (2006), the variation in embodied energy values is still unresolved. There is no standardized method for embodied energy assessment that would reduce some of these variations (Menzies et al., 2007; NIST, 2010). The International Standardization Organization (ISO) developed standards (ISO14040 and ISO 14044) for Life Cycle Assessment (LCA) of a manufactured product. However, these standards have been criticized for not being able to provide required guidance to streamline the LCA process (Zamagni et al., 2008; Weidema et al., 2008; Heijungs et al., 2009; Jeswani et al., 2010). Some of the parameters responsible for variations have been identified, and can be used to develop a set of

guidelines to streamline the process of embodied energy calculation (Dixit et al., 2010).

Embodied energy research lacks a standard methodology to accurately assess the energy embodied of a building (Ting, 2006; Menzies et al., 2007; Langston and Langston, 2008; Frey, 2008; Khasreen et al., 2009). Existing methods are either incomplete or not specific to provide accurate embodied energy values. Based on the literature review, it is important to derive a holistic system for defining an accurate system boundary. Moreover, there is an urgency to develop a user-friendly method for calculating the embodied energy to reduce the variations in embodied energy data due to methodological and data quality parameters.

3 Research Methodology

3.1 Rationale for Case Study

The literature review illustrated that there has been a vast amount of research on embodied energy calculation, system boundary model, and variations in embodied energy data. I collected, analyzed, and used relevant information from previous studies in order to fill the identified research gaps. This research aims at defining the environmental impacts due to building material selection, through the quantification of material embodied energy and carbon dioxide emissions of a high-performance building. The case study approach limited to the assessment of the embodied energy and carbon emissions of the structural materials and photovoltaic system of a high-performance building facilitated a detailed calculation of the selected materials environmental costs, guarantying a high level of accuracy in comparison with publicly available databases.

A primary question that I address is: ***How is the embodied energy of building materials assessed and reduced during the architectural design process?***

To calculate the embodied energy and carbon emissions of structural materials, the following have to be considered: 1) material quantities; 2) energy consumed during the manufacture of building materials; 3) distance traveled to construction site; and 4) transportation energy required to move materials to the site. A quantitative approach was chosen to assess the embodied energy and carbon emissions associated with the structural materials of high-performance buildings. I selected a case study - The Aldo Leopold Legacy Center in Baraboo, WI - to accurately calculate the embodied energy and carbon emissions of structural materials, and the environmental cost saving of material substitution. The case study selection was based on the following criteria:

1. The building is carbon neutral in operation; when high-performance buildings approach net zero

energy demand and carbon neutral operation, the embodied energy and CO_2 emissions due to building construction become a much more significant part of the total building energy life cycle costs.

2. Detailed documentation of the construction process. Detailed records of construction allowed for future analysis of embodied energy and carbon dioxide emissions due to construction, including the analysis achieved in this research.
3. The Aldo Leopold Legacy Center is unique in that the owner provided over 70% of the wood used in construction, where wood was harvested from the pine forest surrounding the site.
4. The design team's practice ethos; the Kubala Washatko Architects embrace a design philosophy of wholeness, where the built environment supports and enhances both human activity and natural living systems. Therefore, the building was designed to fit within its ecological landscape, using materials that will age gracefully over time. Additionally, the project delivery method employed was design-build, making on-site design changes to provide substantial energy savings relatively simple.
5. The Legacy Center was designed and constructed under the USGBC's LEED NC 2.0 rules, which included requirements for documentation of recycled content in materials, substitution of materials (fly ash and slag for cement) and certification of sustainably managed forest and timber harvests. This thorough documentation in addition to the owner's material tracking made this study possible.
6. The vital role of the owner (Aldo Leopold Foundation) in energy-saving design decisions.

3.2 Research Strategy & Scope

This research is limited to embodied energy and carbon emission assessment of structural

materials and the photovoltaic system due to a number of reasons. First, the exclusion of interior partitioning, finishing, and other non-structural materials, allows the focus on the structural design, which is influenced by location, materials, design codes and engineering design (Knight and Addis, 2011; Vukotic et al., 2010). Second, structure constitutes the largest quantity and weight in buildings and contributes about half of the embodied energy and carbon emissions of total materials (Kaethner and Burridge, 2012). Moreover, while the photovoltaic array is a high-tech system and with embodied energy and processing, this system generates energy on-site and results in reducing operational energy. Lastly, limiting the scope of this research to the study of structural materials and PV system allowed for a more detailed analysis embodied energy and CO_2 emissions of materials and components studied.

3.3 Data Collection

As mentioned above, estimation of embodied energy and carbon emissions of structural materials requires knowledge of material quantities, materials manufacturing energy, distance traveled to construction site, and transportation energy required to move materials to the site. The following five sources were used to obtain required data for conducting this research.

Figure 15: Structural Steel Connectors
Source: Aldo Leopold Foundation BIM Model

3.3.1 BIM Model

The process of energy estimation began with dissecting the building into its structural elements.

The Revit model provided volumes of the materials studied in this research, including concrete, steel, and masonry. An example that shows obtained volumes of different steel connectors is shown in Figure 15. Obtaining these volumes facilitated the estimation of embodied energy and carbon emissions associated with these materials, and resulted in increased accuracy.

3.3.2 Building Documentation

Quantities of a number of the building's components were generated from the construction documents provided by the design team and general contractor. This provided accurate quantification of steel reinforcement used. Additionally, the construction documents were used to verify material quantities derived from the BIM model. Figure 16 for example, identifies concrete footing types. Volumes were calculated separately for each concrete mix, and the sum of the values obtained was

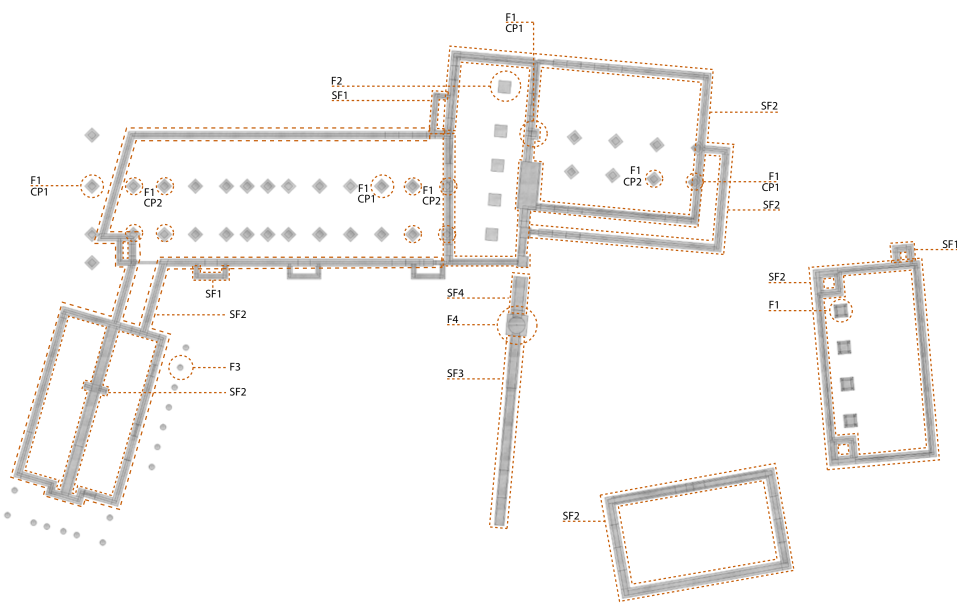
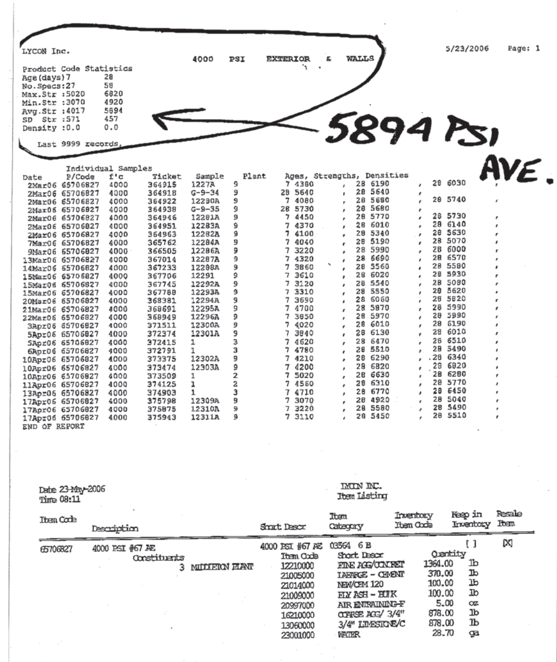


Figure 16: ALF Concrete Footings
Source: By Author

compared to the BIM values. A similar process was used to calculate volumes of concrete interior floors and concrete retaining walls.

3.3.3 LEED Documentation

The case study selected was a high-performance building designed and constructed under the USGBC's LEED NC 2.0 rules, which included requirements for documentation of recycled content in materials, substitution of materials (fly ash and slag for cement) and certification of sustainably managed forest and timber harvests. The availability of this information facilitated the detailed estimation of embodied energy and CO_2 emissions for the materials studied. (Figure 17) is an example of LEED documentation indicating detailed content of a concrete mix, including fly ash, slag, cement and aggregate.


LYCON Inc. 4000 PSI EXTERIOR & WALLS 5/23/2006 Page: 1

Product Code Statistics

Age(days)	7	28
No.Specs:	27	58
Max.Str :	5020	6820
Min.Str :	3070	4920
Avg.Str :	4017	5894
SD Str :	571	457
Density :	0.0	0.0

Last 9999 records,

5894 PSI AVE.

Individual Samples

Date	P/Code	f'c	Ticket	Sample	Plant	Ages, Strengths, Densities		
2Mar06	65706827	4000	364915	1227A	9	7 4380 ,	28 6190 ,	28 6030 ,
2Mar06	65706827	4000	364918	G-9-34	9	28 5640 ,	28 5640 ,	
2Mar06	65706827	4000	364922	12280A	9	7 4080 ,	28 5680 ,	28 5740 ,
2Mar06	65706827	4000	364938	G-9-35	9	28 5730 ,	28 5680 ,	
2Mar06	65706827	4000	364946	12281A	9	7 4450 ,	28 5770 ,	28 5730 ,
2Mar06	65706827	4000	364951	12283A	9	7 4370 ,	28 6010 ,	28 6140 ,
2Mar06	65706827	4000	364963	12282A	9	7 4100 ,	28 5340 ,	28 5630 ,
7Mar06	65706827	4000	365762	12284A	9	7 4040 ,	28 5190 ,	28 5070 ,
9Mar06	65706827	4000	366505	12286A	9	7 3220 ,	28 5990 ,	28 6000 ,
13Mar06	65706827	4000	367014	12287A	9	7 4320 ,	28 6690 ,	28 6570 ,
14Mar06	65706827	4000	367233	12288A	9	7 3860 ,	28 5560 ,	28 5580 ,
15Mar06	65706827	4000	367706	12291	9	7 3610 ,	28 6020 ,	28 5930 ,
15Mar06	65706827	4000	367745	12292A	9	7 3120 ,	28 5540 ,	28 5080 ,
15Mar06	65706827	4000	367788	12293A	9	7 3310 ,	28 5550 ,	28 5620 ,
20Mar06	65706827	4000	368381	12294A	9	7 3690 ,	28 6060 ,	28 5820 ,
21Mar06	65706827	4000	368691	12295A	9	7 4700 ,	28 5870 ,	28 5990 ,
22Mar06	65706827	4000	368949	12296A	9	7 3850 ,	28 5970 ,	28 5990 ,
3Apr06	65706827	4000	371511	12300A	9	7 4020 ,	28 6010 ,	28 6190 ,
5Apr06	65706827	4000	372374	12301A	9	7 3840 ,	28 6130 ,	28 6010 ,
5Apr06	65706827	4000	372415	1	3	7 4620 ,	28 6470 ,	28 6510 ,
6Apr06	65706827	4000	372791	1	3	7 4780 ,	28 5510 ,	28 5490 ,
10Apr06	65706827	4000	373375	12302A	9	7 4210 ,	28 6290 ,	28 6340 ,
10Apr06	65706827	4000	373474	12303A	9	7 4200 ,	28 6820 ,	28 6820 ,
10Apr06	65706827	4000	373509	1	2	7 5020 ,	28 6630 ,	28 6280 ,
11Apr06	65706827	4000	374125	1	2	7 4560 ,	28 6310 ,	28 5770 ,
13Apr06	65706827	4000	374903	1	3	7 4710 ,	28 6770 ,	28 6450 ,
17Apr06	65706827	4000	375798	12309A	9	7 3070 ,	28 4920 ,	28 5040 ,
17Apr06	65706827	4000	375875	12310A	9	7 3220 ,	28 5580 ,	28 5490 ,
17Apr06	65706827	4000	375943	12311A	9	7 3110 ,	28 5450 ,	28 5510 ,

END OF REPORT

Date 23-May-2006
Time 08:11

LYCON INC.
Item Listing

Item Code	Description	Short Descr	Item Category	Inventory Item Code	Keep in Inventory	Resale Item
65706827	4000 PSI #67 AE	4000 PSI #67 AE	03564 6 B		[ ]	[X]

Constituents
3 MIDDLETON PLANT

Item Code	Short Descr	Quantity	
12210000	FINE AGG/CONCRET	1364.00	lb
21005000	LAFARGE - CEMENT	370.00	lb
21014000	NEW/CEM 120	100.00	lb
21009000	FLY ASH - BULK	100.00	lb
20997000	AIR ENTRAINING-F	5.00	oz
16210000	COARSE AGG/ 3/4"	878.00	lb
13060000	3/4" LIMESTONE/C	878.00	lb
23001000	WATER	28.70	ga

Figure 17: LEED Documentation Sample
Source: Courtesy of Boldt Construction

3.3.4 Environmental Material Databases

Energy and carbon data that could not be calculated was collected from the Inventory of Carbon and Energy (ICE) developed by the University of Bath. This inventory is a database of embodied energy and embodied carbon coefficients for building materials. It contains 1,700 records on embodied energy, and is structured into 34 main material groups (aggregates, aluminum…etc.). Data collection sources included journal articles, Life Cycle Assessments (LCA's), books, and conference papers, among others. The ICE-Database was created to obtain the "best" selection of coefficients; it stores relevant information from the literature in which it is based on, including country data, year, boundaries, and data sources.

3.3.5 Interviews

Information relating to transportation distances, manufacture of materials, and building construction was obtained through interviews with sub-contractors. Cement manufacture and transportation details were provided by Lafarge North America Cement. The owner provided data on the building construction and operational energy of the building studied. Information on the design and construction management practices as they influenced material selection decisions were obtained through interviews with the architect. Additional building construction and material information was collected through interviews with wood harvesters, site excavator, and local carpenters.

3.4 Limitations

There was no standard method for the collection of data concerning the type, number, and specifications of components used in the building, their transport to the site, the construction energy. Data collection depended on the methods approach and boundaries I selected for the study. My research was limited to a cradle to site life cycle system boundary; it considers all activities starting with the extraction of materials from the earth (the cradle), their transportation, refining, processing, and fabrication activities until the material is ready to leave the factory gate, and the transportation of the material to its site. This study does not account for material waste resulting from construction on site. Moreover, this study relied on available material databases for the calculation of embodied energy and carbon emissions for a number of materials, which may result in inaccuracies. Lastly, the research was limited to the embodied energy and carbon emission estimation associated with structural materials; my study did not encompass all materials and building components.

4 Case Study

4.1 Leopold & the "Land Ethic"

Aldo Leopold was a conservationist, philosopher, and educator who developed an interest in the natural world at an early age. This interest led him to study ecology and the significance of conservation in protecting biodiversity and endangered species. In 1933, Leopold published the first textbook in the field of wildlife management. In late winter 1935, Aldo Leopold purchased an abandoned farm bordering the Wisconsin River. With his family Leopold cleaned and repaired the chicken coop on the farm, transforming it into a weekend retreat referred to as "the shack". The family spent weekends observing nature, hunting, and healing the land. Over the first decade they planted white and red pines in the worn-out farm fields. The shack was the setting for Aldo Leopold's "A Sand County Almanac" (Leopold, 1949), which was published a year after his death. A Sand County Almanac is a collection of essays that examine the relationship of humans with the natural world and the importance of treating land with the respect it deserves. The finale to this publication is Leopold's "Land Ethic" essay, which calls for moral responsibility to the natural world. The core idea of a land ethic is caring and respecting both people and land. It expands the

Figure 18: Aldo Leopold, 1940s
Source: www.aldoleopold.org

Figure 19: The Leopold Shack, 1936
Source: www.jillmetcoff.com/folio/leopold/1.html

definition of "community" to include not only humans, but also soils, waters, plants, and animals. Leopold believed that direct contact with the natural world was crucial in shaping our ability to extend our ethics beyond our own self-interest. He wrote his essays in an effort to inspire others to explore nature and develop an ethic of care that would grow out of their own personal connection to nature (aldoleopold.org, accessed 2016).

> ***"When we see land as a community to which we belong, we may begin to use it with love and respect."***

4.2 Setting

The farm that served as Aldo Leopold's conservation experiment is now owned by the Leopold Foundation. This foundation was established in 1982 to foster the land ethic through the legacy of Aldo Leopold,. It aimed to create a legacy center that would be a model for environmental stewardship. Buddy Huffaker, the foundation's director and Nina Leopold (Aldo Leopold's daughter) envisioned a low-volume, high-intensity experience that would help people come into greater contact with the land and get a deeper appreciation of the land ethic (Eco-structure, 2009). At the end of the 20th century, the foundation built a new facility on land near "the shack" using pines harvested in the forest thinning for the new building's structure. The design process was initiated with a goal-setting meeting attended by representatives of the foundation board, the foundation's commissioning agent and design team, including architects, engineers, environmental consultants and energy simulation engineers. The board stated that the building should be carbon neutral to reflect the environmental mission of the foundation. This required the architect and environmental consultant to develop the spatial program and research existing high

performance buildings. Since data on the carbon emission cost of the construction was not readily available, especially for manufactured products, the boundary for carbon neutrality would be for operation of the building. Operation was broadly defined to include employee travel as well as all foundation activities that generated emissions on the site. In addition, the design was envisioned to produce a net zero-energy building. Annual renewable energy production on site would be equal or greater than annual building energy demand, with electricity and biofuels (wood) as the only energy sources for building operation (Utzinger & Bradley, 2009).

4.3 High-Performance Attributes

Figure 20: The Aldo Leopold Legacy Center
Source: Courtesy of the Kubala Washatko Architects, Inc

The Aldo Leopold Legacy Center was designed to last at least 100 years; every design decision was made with a view toward the long-term sustainability. The building received LEED Platinum certification in 2007, which included the first ever innovation and design point for carbon neutral operation. The main building's shell was constructed of durable materials, and the structure was left exposed in the interior spaces reducing the need for finish materials that required maintenance. The project sought to fit within its ecological landscape, and was constructed with timber milled from the 1,500 acre Leopold Memorial Reserve where the building sits. The

Leopold pines, which were showing signs of stress, were thinned to maintain their health. This site-harvested wood was milled on-site and used in structural timber, doors, and windows. Local sourcing addressed the team's goal for a carbon-neutral building. Approximately 90,000 board feet of site-harvested lumber was milled and dried locally for window frames, doors, siding, flooring, and paneling. Pine trees were debarked on-site, air-dried, and used to construct innovative round-wood rafters and trusses. Almost the entire timber skeleton of the Legacy Center was built with Leopold pines; 78% of all wood used in the project is Forestry Stewardship Council (FSC) certified.

The site's geology, including more than 300 feet of sand, encourages natural percolation of rainwater. Therefore, the design team sought to harvest all rainwater on site. The use of crushed gravel in place of asphalt or concrete paving minimized impervious areas and, increased rainwater infiltration and resulted in blending developed areas into the surrounding landscape. Rainwater captured from the roof was channeled through an aqueduct into a rain garden planted with native species (aiatopten.org/node/135). To save energy, the heating and cooling systems were separated by an underground earth tube system that reduced the amount of air to the building. The tubes (Figure 21) were constructed of 24-inch diameter concrete pipes buried about 10-12 feet deep. Surrounded by earth, the tubes moderate and maintain a steady air temperature of approximately 55 degrees year-round, which ultimately reduces heating and cooling costs (Countymaterials.com, accessed 2017). The Legacy Center was designed to use 70% less energy than a comparable conventional building (aiatopten.org/node/135). A 39-

Figure 21: Leopold Center Earth Tubes
Source: The Kubala Washatko Architects, Inc

kWh solar photovoltaic array (Figure 22) on the roofs generates more than 61,000 kWh of electricity annually. Additionally, the roof is designed to bounce daylight into the interior spaces, reducing the need for artificial light. Wide overhangs shield the direct sun in the summer yet allow passive gain in the winter.

Figure 22: Photovoltaic System
Source: Aldo Leopold Foundation

Geothermal radiant heating and cooling also contribute to mechanical efficiency. Another energy saving decision was grouping offices with similar temperature preferences on the same coil loops set within radiant floors; smaller coil loops avoid water circulation across the entire floor to heat the space. The main building's long and narrow footprint allows for natural ventilation and daylighting. A south-facing minimally conditioned thermal flux zone provides a buffer to staff areas and allows occupants to manage natural ventilation, solar gain, and glare. Overhangs shield the interior from direct sun in the summer but allow passive solar gain in the winter.

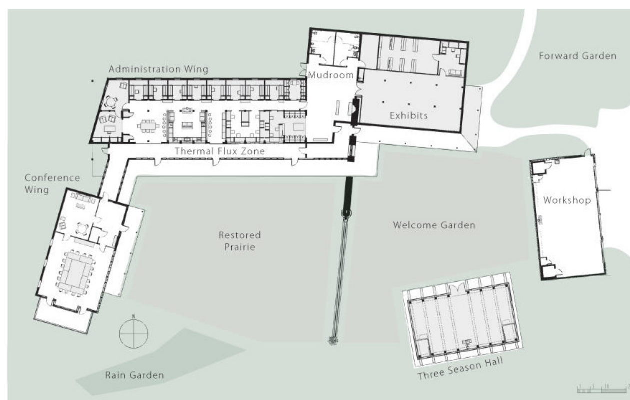


Figure 23: ALF Floor Plan
Source: http://www.aiatopten.org/node/135

The roof maximizes solar electricity production and bounces indirect light into the building, and the building envelope minimizes thermal transfer. Private staff spaces provide acoustical separation from public spaces and allow occupants to control airflow, cooling, and daylighting. More than half of the Aldo Leopold's Legacy Center's energy savings are realized through low-tech, high-yield design strategies, most of which could be summarized in Figure 24. The

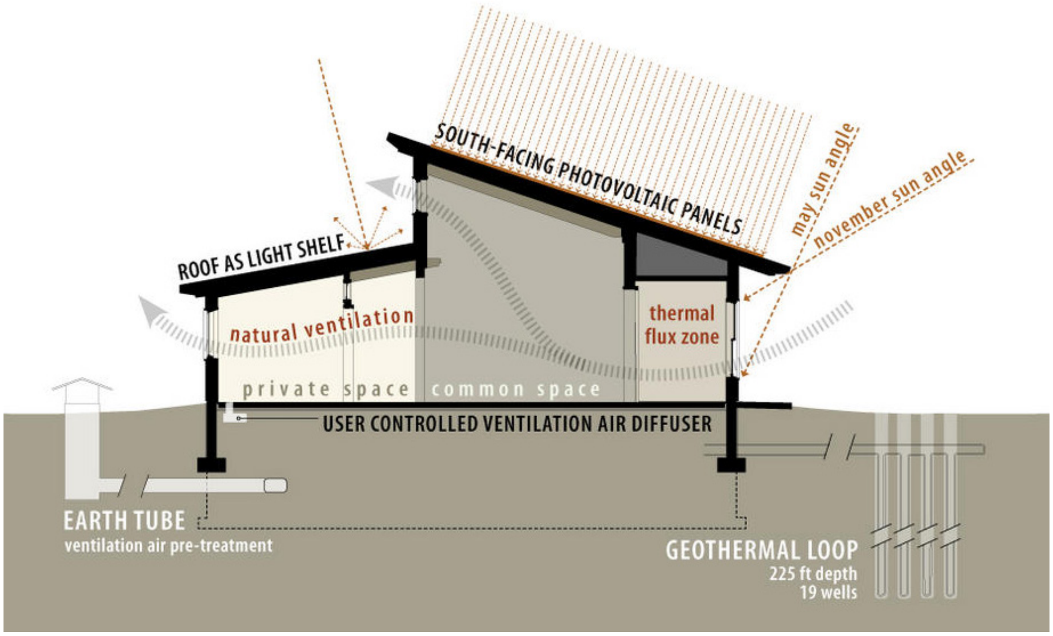


Figure 24: ALF Low-Tech Design Strategies
Source: http://www.aiatopten.org/node/135

building performs with low mechanical assistance and minimum user effort throughout the year. The availability of Leopold wood was a unique opportunity, however the process in which the project team engaged in the design of the Legacy Center is replicable and provides a model for the construction of other buildings. The building's high-performance attributes are a result of rigorous analysis of its energy use and carbon footprint, innovative approach to natural ventilation, use of locally harvested and recycled-content materials, and a small ecological footprint. A great example of the architect's ecological approach to design was the use of reclaimed stone from a demolished airplane hangar in Truax field, Madison to construct the hearth of the building (Figure 25,26).

Simulation modeling during the design process was used to evaluate the sizing of the building's individual HVAC components and control strategies. At the beginning of the design process, the simulation program TRNSYS was adopted by the Legacy Center's environmental consultant (Utzinger & Bradley, 2009) to provide feedback on the expected performance of the building. Unlike current simulation programs integrated with BIM models providing quick

Figure 25: Truax Field, Madison, WI. 1937 (Demolished)
Source: wisconsinhistory.org

Figure 26: Aqueduct
Source: Courtesy of Michael Utzinger

evaluations on energy implications of design decisions, TRNSYS (Klein, et al., 2005) allows time steps in the range of control feedback and permits integration of components as needed. In other words, TRNSYS allows for modeling complex control strategies such as the integration of natural ventilation decisions controlled by the occupant and earth tube heat exchangers (Hullmuler, 1998) .

4.3.1 Modeled and Measured Energy Performance

The energy simulation model provided the design team an estimation of the building's operational energy and whether the goal set for net-zero design was achievable. The model was also used to provide energy use requirements for LEED version 2.1 certification (Utzinger & Bradley, 2009). A requirement for LEED certification of environmental performance of buildings, energy savings are estimated through the comparison of energy requirements estimated by building simulation (Design Energy Case or DEC model) with code energy requirements (Energy Cost Budget or ECB

model). Additionally, a third model was developed (Carbon Neutral Case or CNC) as part of LEED's Innovation and Design credit for carbon neutral buildings. A comparison of the output of the three aforementioned models is shown in Table 03. The total energy demand of LEED's DEC model is 47.4% of the code based model (ECB) energy demand. The CNC model has a total demand of 41.4%

	ECB Model	DEC Model	CNC Model
Total Energy	131,040	62,100	54,230
Unregulated Energy	11,680	11,680	11,680
Total Regulated Energy	119,360	50,420	42,550
Illumination	26,370	21,820	13,400
Space Heating	75,330	16,922	18,260
Space Cooling	4,340	3,150	2,320
Pumps	4,760	2,870	2,890
Fans	6,150	4,930	4,930
Service Water Heating	2,420	710	730
Renewable Energy	0	61,250	61,250
Net Regulated Energy Demand	119,360	-10,830	-18,700
Net Energy Demand	131,040	850	-7,020

Table 03: LEED DEC and ECB Model Comparison w/ CNC Model
Source: Utzinger & Bradley, 2009

of the ECB energy model demand; it predicts that occupant control of lights will reduce the Legacy Center's energy demand (Utzinger & Bradley, 2009). Moreover, the CNC model predicts annual electricity production from the photovoltaic system to be 12.9% of the annual energy demand, giving the design team confidence that the building will meet net-zero design goal (Utzinger & Bradley, 2009).

The Leopold Foundation's controls system was structured to archive energy data. Two meters were installed, one measuring electricity produced on site (photovoltaic panels) that exceeds building demand and is distributed to the grid, and one to measure electricity from the grid consumed in the building (Utzinger & Swenson, 2012). Metering allowed the collection of detailed performance data for actual building performance analysis. The net monthly simulated and measured electricity

consumption for the years 2008 through 2010 is illustrated in Figure 27. Electricity flowing from the building to the grid is defined as positive, and electricity flowing from the grid into the building is

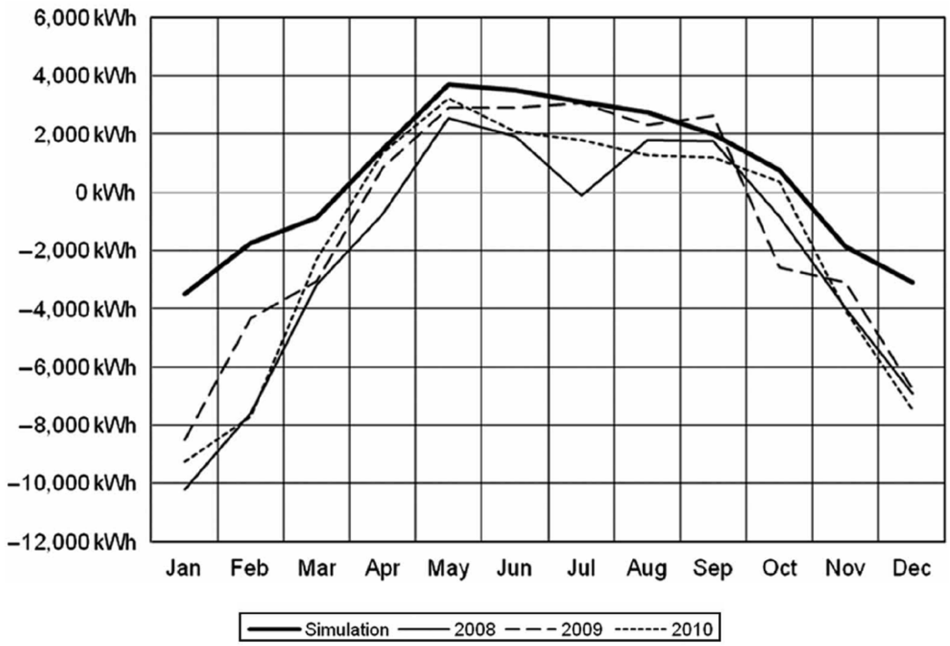


Figure 27: Modeled and Measured Monthly Energy Demand
Source: Utzinger, 2012

negative. The net energy flow measured for the years (2008-2010) was -22.3 kWh/m^2, -11.8 kWh/m^2, and -17.0 kWh/m^2 respectively, missing the net zero energy goal. Falling short of the design team's net zero energy goal is attributed to the fact that measured plug loads were greater than estimated, and snow covering the PV system in the winter; annual snowfall totals during the past four winters exceeded average values. Although the Leopold Legacy Center fell short of achieving its goal of net zero energy, the net consumption of 17 kWh per m^2 is only 5.8% of the average U.S. office building and 14.8% of the energy required if the building was code compliant (Utzinger & Swenson, 2012). This building is an interpretation of Aldo Leopold's land ethic, demonstrating that when designers consider a building as part of a larger ecological community, the carbon emissions of building operation can be minimized.

5 Material Assessment

5.1 Introduction

In 1890, London held a tower design competition with material weight of the structure as one of the design criteria (Figure 28) (Lynde, 1890). Later in the 1920s, Buckminster Fuller raised the question "How much does your house weigh?" (Braham & Hale, 2013), emphasizing material efficiency in building design. Recently, studies have attempted to map material efficiency of tall buildings considering the number of floors and structural systems (Cho et al., 2004; Elnimeiri and Gupta, 2009; Ali and Moon, 2007). Data on material quantities from leading structural design firms

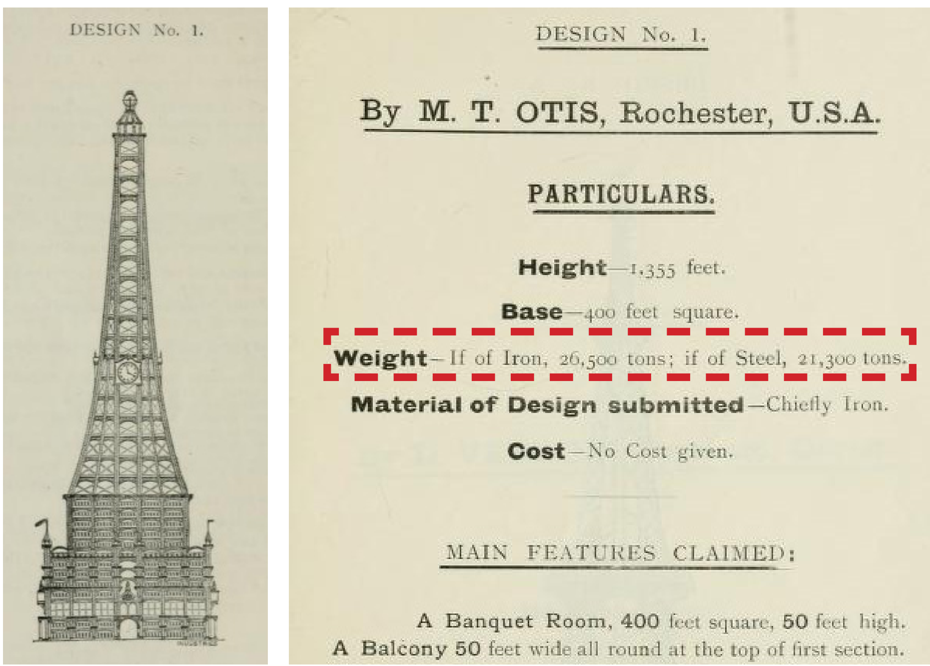


Figure 28: Design Entry in the 1890 London Tower Competition
Source: Lynde, 1890

such as Arup and Thornton Tomasetti, have been collected in the material quantity and the database of embodied Quantity outputs (deQo), developed at the Structural Design Lab within the Building Technology program at MIT (De Wolf & Ochsendorf, 2014; deQo, 2014).

Structure constitutes the largest weight in buildings and contributes to roughly half of the

total carbon emissions due to materials manufacture (Webster et al., 2012). Moreover, Kaethner and Burridge (2012) demonstrated that the super- and substructure together accounts for approximately half in a breakdown of embodied energy for the different elements in offices, hospitals and schools (Figure 29). The proportion of structural materials in a building can be up 70 - 90% of the weight. A timber and steel building has the lowest percentage weight, whereas brick and concrete have the

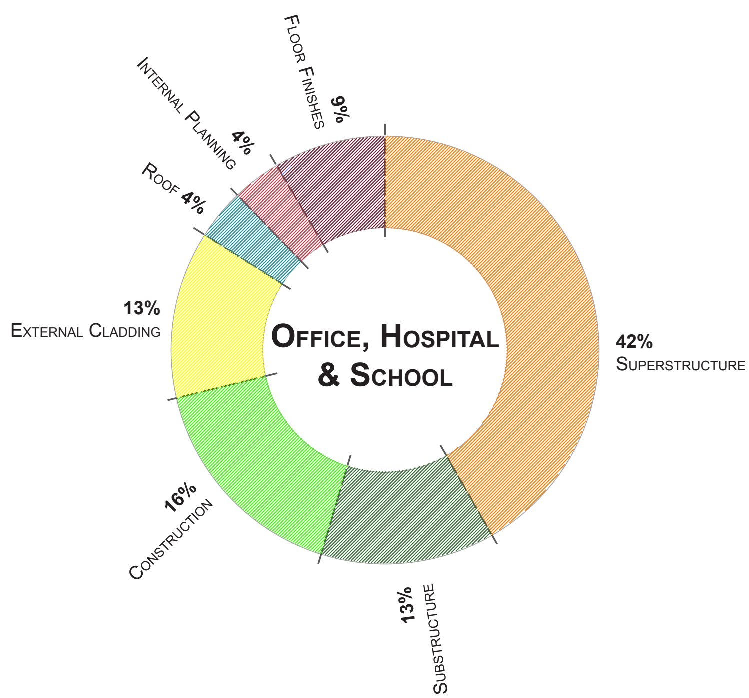


Figure 29: Average breakdown in building elements of EE
Source: By Author, based on Kaethner & Burridge (2012)

highest (Berge, 2009). Given that the structural materials in a building make up the greatest percentage of total weight and contributes to more than half of the carbon emissions, this research is limited to the embodied energy assessment of the structural materials in the Aldo Leopold Legacy Center. Therefore, non-structural materials were not considered in this assessment for three reasons. First, structure constitutes the largest weight in buildings and contributes to approximately half of the total carbon emissions of total building materials. Second, the studied structural materials are aspects that architects and designers can control of when making design decisions and material

selection. Third, limiting the EE assessment to structural materials allows the focus on a well-defined quantity while still having a significant impact (Wise et al., 2013). Structural materials based on renewable resources such as timber provide less negative environmental impacts per unit of weight than other building materials (Berge, 2009).

5.2 Concrete

The global demand for cement and concrete increased exponentially in the last 20 years due to population growth and an increased need for buildings and infrastructure (Ahmaruzzaman, 2010; Gibbs, 2001; Hasanbeigi et al, 2012). Cement production grew from 594 Mt (Megaton) in 1970 to 2,284 Mt in 2005 globally, with the majority of growth occurring in developing countries especially China with 47% of world cement production. In 2009, more than 3 billion tonnes of cement were produced worldwide (Feiz et al, 2014). Although concrete is widely used due to its durability, availability, and conventional construction methods, the manufacturing of cement is an energy-intensive process. Cement is produced by heating limestone (calcium carbonate) with other materials such as clay to 1450 °C in a kiln in a process known as calcination. It is then chemically blended with the other materials included in the mix to form calcium silicates and other cementitious compounds. The resulting material is referred to as "clinker", and is ground with a small amount of gypsum into a powder to make the most commonly used type of cement referred to as "Portland cement". For every one-ton cement produced one-ton CO_2 is emitted (Chen et al., 2010; Ramezanianpour, 2014; Sales & Lima, 2010).

5.2.1 Material Substitutions

To reduce the carbon dioxide emissions associated with cement production, supplementary

cementitious materials (SCM) are used to replace cement in concrete mixes. Clinker in concrete mixes is replaced with these supplementary materials, which reduces the consumption of resources and energy, and avoids CO_2 environmental impacts associated with cement production. Fly ash is one of the most ubiquitous of the supplementary materials and has been used for the past 80+ years in cement applications (Vargas & Halog, 2015). Volcanic ash was used by the ancient Romans in concrete, and fly ash has been used in pozzolan (a material that has cementitious properties) in concrete since the construction of the Hoover Dam in 1929.

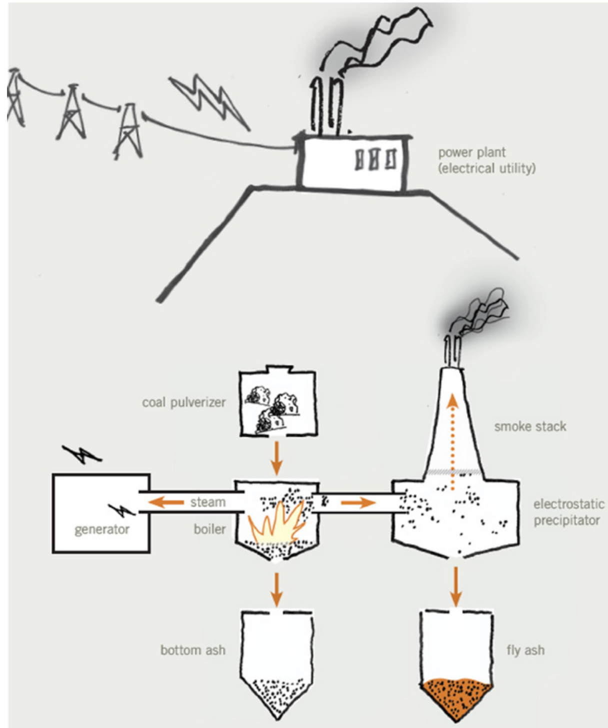


Figure 30: Coal Fueled Power Plant
Source: Perkins & Will White Paper, 2011

Significant quantities of coal ash result when coal is burned. The lighter ash, which is the dust that rises up the flue when coal is burned, is what is referred to as fly ash (Figure 30). Rather than sending this ash to landfills, some of it is recycled and used as an additive in building products. Fly ash is a common ingredient in concrete, carpet backing, recycled plastic lumber, grout, acoustic ceiling tiles, and other building materials. Of all the building materials in which fly ash is used, concrete gets special consideration. Fly ash mixed with concrete accounts for approximately 7% of the fly ash diverted from landfills every year (Perkins & Will White Paper, 2011). There are performance benefits to using fly ash in concrete; it improves plasticity, decreases permeability, increases sulphate resistance and enhances durability. Each year, fly ash replaces approximately 8% of Portland cement in concrete in the U.S., and 25% in some European countries.

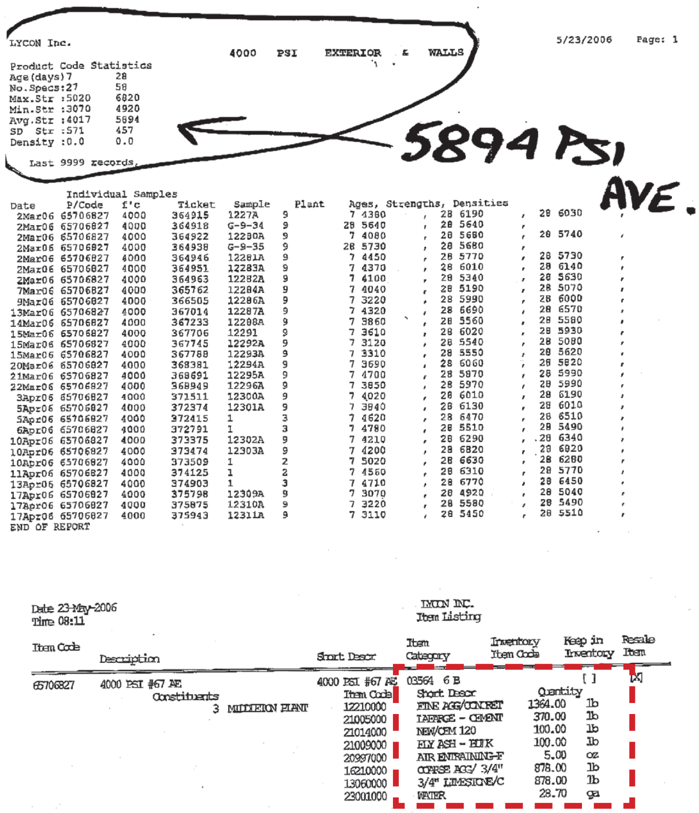
Slag cement, referred to as “slag”, is another supplementary cementitious material used in concrete in place of Portland cement. Slag is a by-product of iron production in a blast furnace. It is a hydraulic cement that can replace between 20 - 80% of Portland cement in concrete and adds to concrete’s sustainable attributes (Slag Cement Association, 2006). Benefits of slag cement include the reduction of virgin material used in the manufacture of concrete, reduction of embodied energy and carbon emissions associated with cement manufacturing, reduction of waste and increasing use of a recovered industrial material, and reducing cementitious material needed to achieve a specified strength. A principal advantage of using slag cement for the reduction of embodied energy and carbon emissions is that substitution rates of slag for Portland cement are relatively high (Table 04). Substitution at these high percentages reduces cementitious requirements, as slag cement concrete would require less cementitious material to achieve a specified ultimate strength. Moreover, high volume substitution with slag cement significantly reduces embodied energy and greenhouse gas emissions in concrete.

Concrete Application	Slag* Cement
Concrete paving	25-50%
Exterior flatwork not exposed to deicer salts	25-50%
Exterior flatwork exposed to deicer salts with w/cm ≤ 0.45	25-50%
Interior flatwork	25-50%
Basement floors	25-50%
Footings	30-65%
Walls & columns	25-50%
Tilt-up panels	25-50%
Pre-stressed concrete	20-50%
Pre-cast concrete	20-50%
Concrete blocks	20-50%
Concrete pavers	20-50%
High strength	25-50%
ASR mitigation	25-70%
Sulfate resistance	
Type II equivalence	25-50%
Type V equivalence	50-65%
Lower permeability	25-65%
Mass concrete	50-80%

**Percentages indicate replacement for portland cement by mass. These replacement rates are suggested for individual applications and are based on historical performance. Variations in material sources and environmental conditions may require alternate substitution rates. Consult your slag cement supplier for additional assistance.*

Table 04: Suggested Slag Substitutions
Source: Slag Cement Association, 2006

Percentages of fly ash and slag substituted cement content in the concrete mixes used in the Aldo Leopold Legacy Center. These percentages were obtained from the concrete specs provided by the general contractor for each of the three concrete mixes. If fly ash and slag were not included in the concrete mix and the cement content increased accordingly, the concrete embodied energy



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Product Code Statistics

Age(days)	7	28
No.Specs	:27	58
Max.Str	:5020	6820
Min.Str	:3070	4920
Avg.Str	:4017	5894
SD Str	:571	457
Density	:0.0	0.0

Last 9999 records,

Individual Samples

Date	P/Code	f'c	Ticket	Sample	Plant	Ages, Strengths, Densities		
2Mar06	65706827	4000	364915	1227A	9	7 4380 ,	28 6190 ,	28 6030 ,
2Mar06	65706827	4000	364918	G-9-34	9	28 5640 ,	28 5640 ,	
2Mar06	65706827	4000	364922	12280A	9	7 4080 ,	28 5680 ,	28 5740 ,
2Mar06	65706827	4000	364938	G-9-35	9	28 5730 ,	28 5680 ,	
2Mar06	65706827	4000	364946	12281A	9	7 4450 ,	28 5770 ,	28 5730 ,
2Mar06	65706827	4000	364951	12283A	9	7 4370 ,	28 6010 ,	28 6140 ,
2Mar06	65706827	4000	364963	12282A	9	7 4100 ,	28 5340 ,	28 5630 ,
7Mar06	65706827	4000	365762	12284A	9	7 4040 ,	28 5190 ,	28 5070 ,
9Mar06	65706827	4000	366505	12286A	9	7 3220 ,	28 5990 ,	28 6000 ,
13Mar06	65706827	4000	367014	12287A	9	7 4320 ,	28 6690 ,	28 6570 ,
14Mar06	65706827	4000	367233	12288A	9	7 3860 ,	28 5560 ,	28 5580 ,
15Mar06	65706827	4000	367706	12291	9	7 3610 ,	28 6020 ,	28 5930 ,
15Mar06	65706827	4000	367745	12292A	9	7 3120 ,	28 5540 ,	28 5080 ,
15Mar06	65706827	4000	367788	12293A	9	7 3310 ,	28 5550 ,	28 5620 ,
20Mar06	65706827	4000	368381	12294A	9	7 3690 ,	28 6060 ,	28 5820 ,
21Mar06	65706827	4000	368691	12295A	9	7 4700 ,	28 5870 ,	28 5990 ,
22Mar06	65706827	4000	368949	12296A	9	7 3850 ,	28 5970 ,	28 5990 ,
3Apr06	65706827	4000	371511	12300A	9	7 4020 ,	28 6010 ,	28 6190 ,
5Apr06	65706827	4000	372374	12301A	9	7 3840 ,	28 6130 ,	28 6010 ,
5Apr06	65706827	4000	372415	1	3	7 4620 ,	28 6470 ,	28 6510 ,
6Apr06	65706827	4000	372791	1	3	7 4780 ,	28 5510 ,	28 5490 ,
10Apr06	65706827	4000	373375	12302A	9	7 4210 ,	28 6290 ,	28 6340 ,
10Apr06	65706827	4000	373474	12303A	9	7 4200 ,	28 6820 ,	28 6820 ,
10Apr06	65706827	4000	373509	1	2	7 5020 ,	28 6630 ,	28 6280 ,
11Apr06	65706827	4000	374125	1	2	7 4560 ,	28 6310 ,	28 5770 ,
13Apr06	65706827	4000	374903	1	3	7 4710 ,	28 6770 ,	28 6450 ,
17Apr06	65706827	4000	375798	12309A	9	7 3070 ,	28 4920 ,	28 5040 ,
17Apr06	65706827	4000	375875	12310A	9	7 3220 ,	28 5580 ,	28 5490 ,
17Apr06	65706827	4000	375943	12311A	9	7 3110 ,	28 5450 ,	28 5510 ,

END OF REPORT

Date 23-May-2006
Time 08:11

LYCON INC.
Item Listing

Item Code	Description	Short Descr	Item Category	Inventory Item Code	Keep in Inventory	Resale Item
65706827	4000 PSI #67 AE	4000 PSI #67 AE	03564 6 B		[ ]	[X]

Constituents
3 MIDDLETON PLANT

Item Code	Short Descr	Quantity	
12210000	FINE AGG/CONCRET	1364.00	lb
21005000	LAFARGE - CEMENT	370.00	lb
21014000	NEW/CEM 120	100.00	lb
21009000	FLY ASH - BULK	100.00	lb
20997000	AIR ENTRAINING-F	5.00	oz
16210000	COARSE AGG/ 3/4"	878.00	lb
13060000	3/4" LIMESTONE/C	878.00	lb
23001000	WATER	28.70	ga

Figure 31: Concrete Mix Specs
Source: Courtesy of Boldt Construction

Footing Mix (5007 psi)		Mass		Manufacturing EE	Manufacturing CE
Aggregate	239,413 kg	216 kg/m^2		18 MJ/m^2	1.1 kg CO2/m^2
Cement	15,947 kg	14 kg/m^2	60.5%	65 MJ/m^2	10.7 kg CO2/m^2
Fly Ash	3,467 kg	3 kg/m^2	13.2%	0.3 MJ/m^2	0.0 kg CO2/m^2
Slag	6,933 kg	6 kg/m^2	26.3%	10 MJ/m^2	0.5 kg CO2/m^2
	265,761 kg	**240 kg/m^2**		**75 MJ/m^2**	**11.2 kg CO2/m^2**
Foundation Wall Mix (6208 psi)					
Aggregate	535,769 kg	484 kg/m^2		40 MJ/m^2	2.5 kg CO2/m^2
Cement	63,537 kg	57 kg/m^2	64.9%	259 MJ/m^2	42.5 kg CO2/m^2
Fly Ash	17,172 kg	16 kg/m^2	17.5%	2 MJ/m^2	0.1 kg CO2/m^2
Slag	17,172 kg	16 kg/m^2	17.5%	25 MJ/m^2	1.3 kg CO2/m^2
	633,651 kg	**573 kg/m^2**		**285 MJ/m^2**	**43.9 kg CO2/m^2**
Interior Floor Slab Mix (6052 psi)					
Aggregate	167,497 kg	151 kg/m^2		13 MJ/m^2	0.8 kg CO2/m^2
Cement	17,738 kg	16 kg/m^2	64.8%	72 MJ/m^2	11.9 kg CO2/m^2
Fly Ash	4,815 kg	4 kg/m^2	17.6%	0.4 MJ/m^2	0.0 kg CO2/m^2
Slag	4,815 kg	4 kg/m^2	17.6%	7 MJ/m^2	0.4 kg CO2/m^2
	194,865 kg	**176 kg/m^2**		**80 MJ/m^2**	**12.3 kg CO2/m^2**
Total Concrete					
Aggregate	942,680 kg	852 kg/m^2		71 MJ/m^2	4.4 kg CO2/m^2
Cement	97,222 kg	88 kg/m^2	64.1%	396 MJ/m^2	65.0 kg CO2/m^2
Fly Ash	25,454 kg	23 kg/m^2	16.8%	2 MJ/m^2	0.2 kg CO2/m^2
Slag	28,920 kg	26 kg/m^2	19.1%	42 MJ/m^2	2.2 kg CO2/m^2
	1,094,276 kg	**989 kg/m^2**		**440 MJ/m^2**	**67.4 kg CO2/m^2**

Table 05: Percentages of ALF Concrete Constituents
Source: By Author

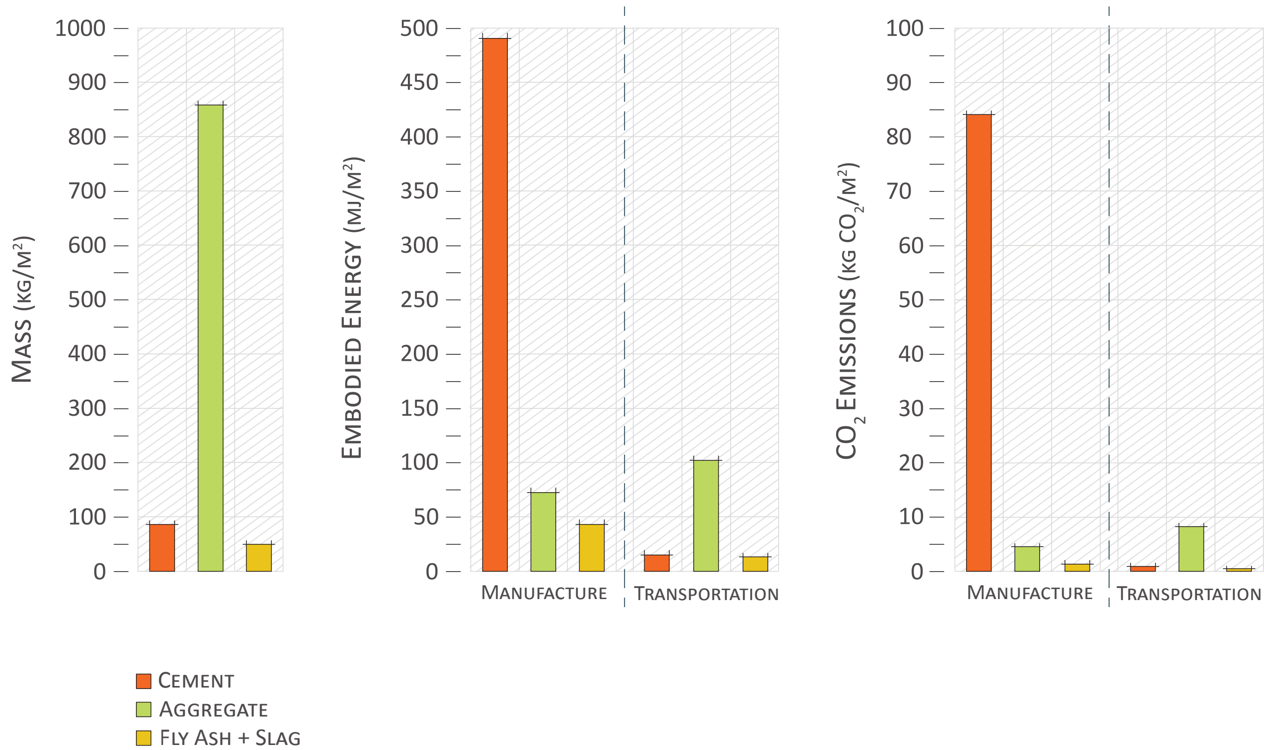
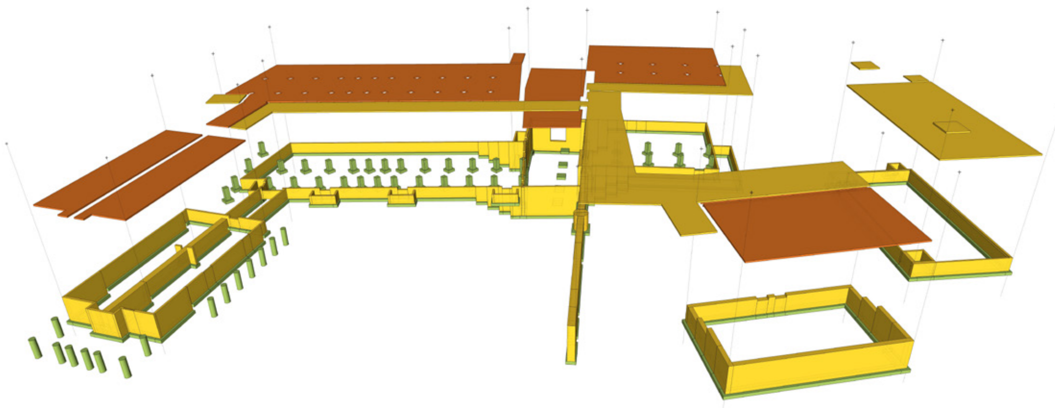


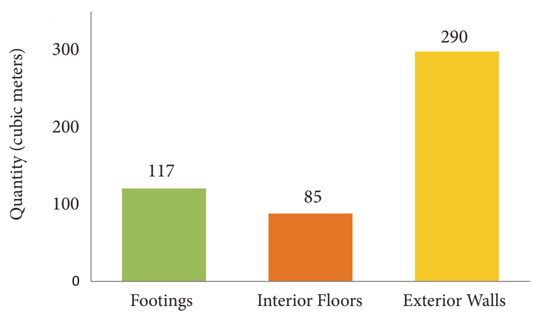
Figure 32: Concrete Mix Comparison
Source: By Author

would increase by 226 MJ/m² and the carbon dioxide emissions by 44.3 kg CO_2/m². Substituting fly ash and slag for a portion of the cement generates significant savings, 17.4% of the total embodied energy and 31.4% of the total carbon dioxide emissions (Figure 32).

5.2.2 Constituents

Three concrete strength and exposure mixes were used in the Aldo Leopold Foundation, a low strength mix for footings, air-entrained mix for foundation walls and exterior slabs, and a medium strength mix for interior floor slabs. Figure 33 shows the volumes for each mix. The aggregate, cement, fly ash and slag masses for each mix were provided in the LEED documentation. Volumes for each mix were determined from the BIM building model. Using that information, the average mass of each concrete constituent in the building was determined. Constituent percentages





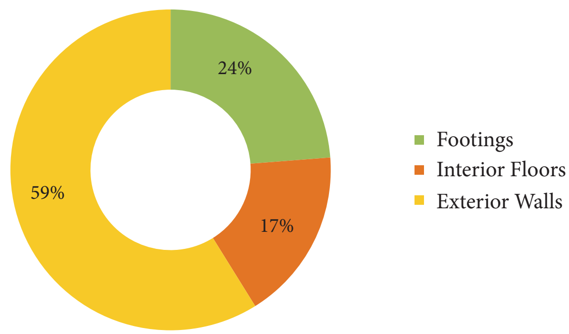


Figure 33: Volume of the Three Concrete Mixes
Source: By Author

by mass are: aggregate 86.1%, cement 8.9%, fly ash 2.3% and slag 2.6% (See Appendix B). The embodied energy and carbon dioxide emissions for concrete components were taken from the Inventory of Carbon and Energy (ICE) Version 2.0 database (Hammond, 2011).

5.2.3 Transportation

Transportation load capacities and fuel efficiencies were provided in interviews with the concrete contractor (Lafarge Cement) and used to estimate the transportation embodied energy. Conversion of transportation fuel consumption to carbon emissions made

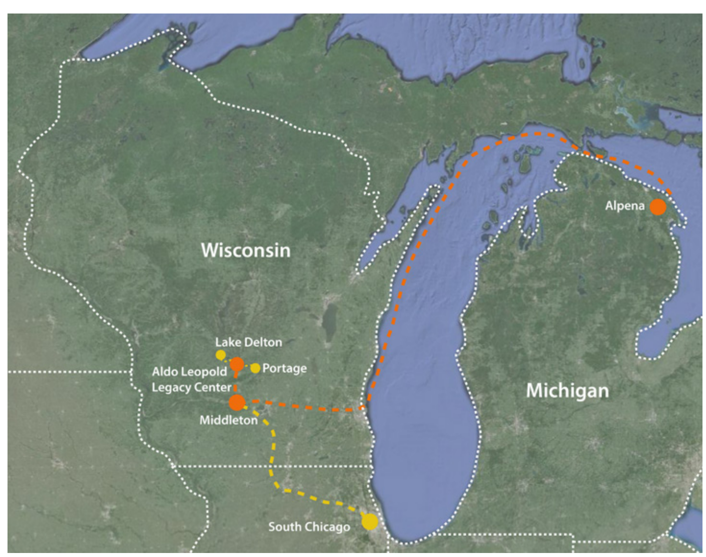


Figure 34: Transportation Route of Concrete Constituents
Source: By Author

use of emission coefficients provided by the US National Renewable Energy Laboratory (Deru, 2007). The aggregate was transported from Lake Delton, WI, a distance of 164 km. Fly ash was transported from Portage, WI a distance of 237 km, while the slag cement was shipped from

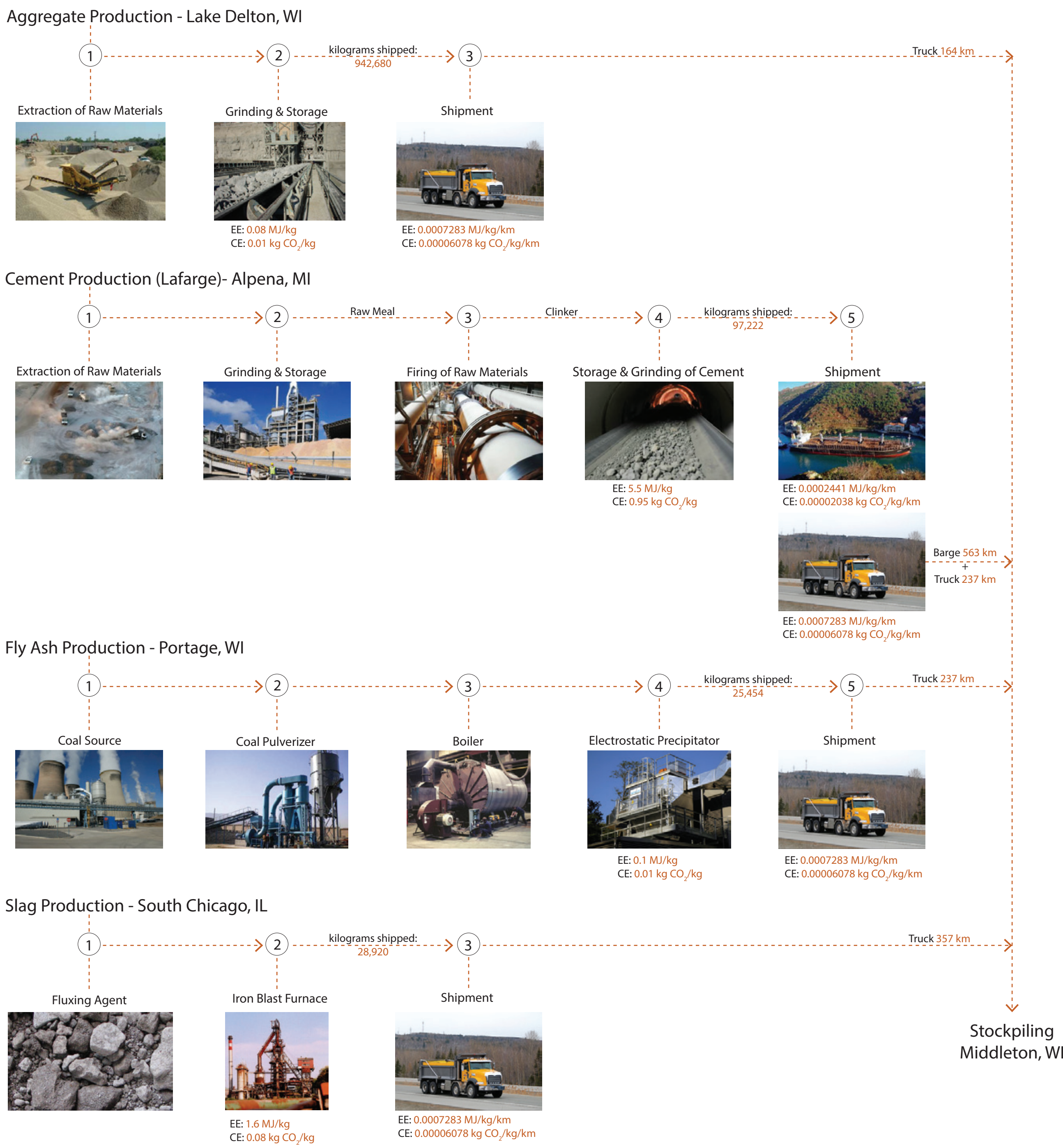


Figure 35: EE + CE Tracking Diagram for Concrete Constituents
Source: By Author

South Chicago a total of 357 km. Of the concrete constituents, the cement is unique in that it was first shipped by barge 563 km from Alpena, Michigan, and then 237 km by truck. Manufacturing embodied energy coefficients were obtained from the ICE database (Figure 35). For concrete, the mass, embodied energy and CO_2 emissions per gross floor area are: 989 kg/m^2, 650 MJ/m^2 and 84 kg CO_2/m^2. Cement is 8.9% of the mass but produces 69.2% of the embodied energy and 84.1% of the CO_2 emissions. The cement's transportation distance was approximately 3 times that of each of the fly ash, slag and aggregate, yet was responsible for only 25% of total transportation embodied energy of the constituents. This is due to the barge's fuel efficiency in comparison with a diesel truck (Figure 36). Moreover, the cement used in the Aldo Leopold Foundation only accounted for a small fraction of the total cement transported on the barge. Therefore it is critical to consider the transportation method and fuel efficiency when shipping a material, in addition to the distance traveled. Section 5.7 compares the embodied energy and carbon emissions of the concrete constituents with the wood, steel and masonry.

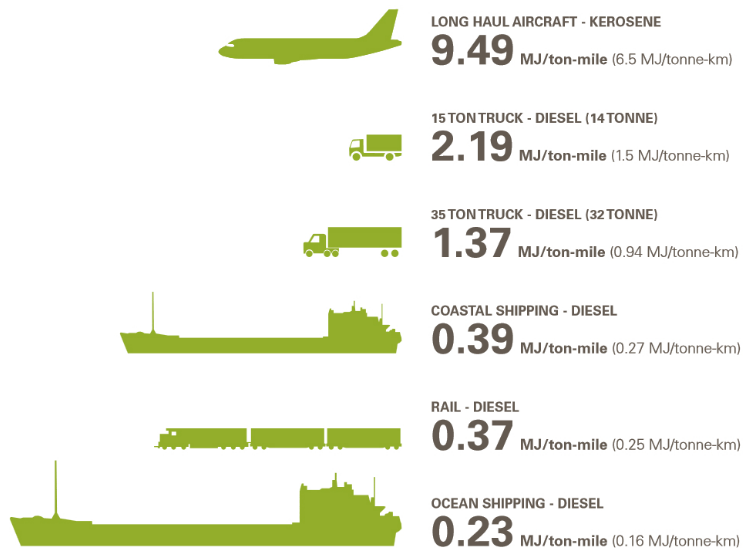


Figure 36: Transportation Energy Comparison
Source: Cannon Design, 2012

5.3 Timber

Wood has been used as a building material for thousands of years. One of the advantages of using wood as a building material is that it is a natural, renewable resource, making it readily available and economically feasible. It is strong in relation to its weight, provides reasonable insulation, and can be fabricated into various shapes and sizes to fit almost any construction need. Moreover, wood is a great example of an environmentally sustainable material; it is biodegradable and renewable, and carries the lowest carbon footprint in comparison to other building materials when processing is minimized.

Wood has a number of advantages over traditional building materials such as concrete and steel. Trees absorb carbon dioxide as they grow. When trees are manufactured into building materials, carbon dioxide essentially remains sequestered in the finished product. Half of the carbon in the tree (roots and branches) is released to the environment. When wooden building materials reach the end of their useful life, they can be re-purposed or recycled into new products. The stored carbon dioxide is kept out of the atmosphere, and may be released at slow rate as a result of the natural biogeochemical carbon cycle. Additionally, wood is low in embodied energy as it is produced naturally and requires far less energy and manufacturing processes compared to other building materials. Energy used to process wood, such as the energy needed for kiln drying, can come from renewable biomass including chips and sawdust. Wood is carbon negative as a result of carbon sequestration, or in other words "storage". One kilogram of wood requires 1.63 kg of carbon dioxide on average and releases 1.11 kg of oxygen. Using wood from sustainably managed forests increases CO_2 removal from the atmosphere. Sustainably grown and harvested wood has a smaller carbon footprint than concrete and steel, making it a good choice for even large buildings. A mass

timber building's carbon footprint is estimated to be 75% less than a concrete and steel building of similar size (greenbuildingelements.com).

5.3.1 Leopold Timber Harvest

Figure 37: Nina Leopold Planting Pine, 1930s
Source: Courtesy of the Aldo Leopold Foundation

A unique feature of the Aldo Leopold Foundation building is the use of wood harvested from the Aldo Leopold managed forests located 1.6 km from the building site. In late winter 1935, Aldo Leopold purchased an abandoned farm bordering the Wisconsin River. With his family Leopold cleaned and repaired the chicken coop on the farm, transforming it into a weekend retreat referred to as "the shack". Over the first decade, Leopold and his family planted white and red pines in the worn-out farm fields. The shack located on the farm became the setting for Aldo Leopold's A Sand County Almanac (Leopold, 1949).

Figure 38: Before (2005) and After (2007) Wood Harvest
Source: Courtesy of the Aldo Leopold Foundation

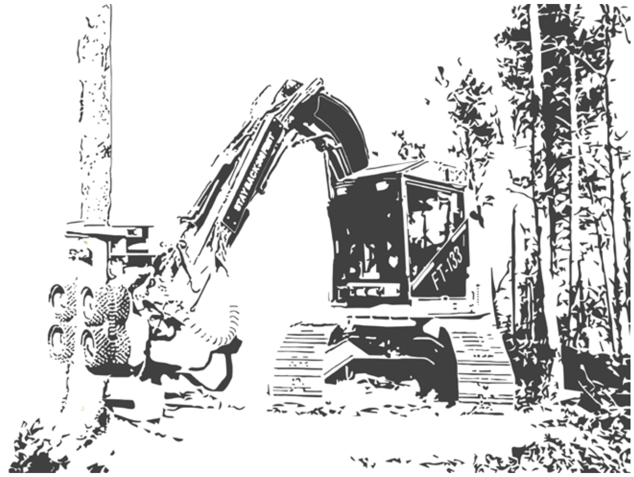


Figure 39: Track Harvester
Source: By Author

The shack, pinewoods and other surrounding lands are now owned by the Aldo Leopold Foundation, established in 1982. In 2003, foresters determined that the Leopold pines were overcrowded and suffering from competition. Drought, disease, wind, or insect outbreaks could be detrimental to the trees health and survival (www.aldoleopold.org). Careful thinning of the smallest trees was recommended by the foresters to restore the forest's health. At the same time, an oak woodland on the property was cut to revert the woodland to Oak savanna, an important yet diminishing part of the southern Wisconsin landscape.

Figure 40: Harvest of Trees Planted by the Leopold Family
Source: www.aldoleopold.org

Not only did the harvests help restore the forests, but they also provided an impressive quantity of high quality wood. At the same time, the Aldo Leopold Foundation had outgrown its office in Baraboo, Wisconsin. A decision was made to build a new facility for the Aldo Leopold Foundation on land near the shack using pines harvested in the forest thinning for the new building's structure. Crafted into columns, beams, and rafters in the Leopold Center, the harvested pine trees frame a space for discovering Leopold's legacy. The impact of the sustainable timber harvest is shown in Figure 38. The pines were harvested using a piece of equipment called a "track harvester" (Figure 39) used to fell and cut the trees. This machine has an articulating arm with the working implement

at the end. The head is set at the base of the tree, two claps hold and secure the tree. At the bottom of the processing head is a cutting head that resembles a chainsaw bar. The bar swings out at the

Figure 41: Pine Harvest
Source: Courtesy of the Aldo Leopold Foundation

push of a button. The tree is cut 3 to 4 inches off the ground with one complete cut (no fiber pull as happens with hand cutting). The tree is then picked up toward a suitable felling lane and is cut to the desired length. The track harvester has minimal impact on the soil, combined with the fact that the harvest took place in the winter when soil is frozen, additionally minimizing the impact.

Leopold Pines were cut into four different products. The butt end of each tree was cut to a length of 17 feet if it was at least 8 inches in diameter on the small end. This was the case for most of the trees. Trees with smaller diameters were likely chosen for whole log construction use and were hand cut. If the diameter was not sufficient for a 17-foot log, the tree was cut into 8 ft. 6 in. lengths. These remaining logs were then sorted for straightness and diameter, with the "best" pieces going to Samsel's sawmill to be made into floor and siding panels. If the sticks were too skinny or crooked, they were sent to Nekoosa to a paper mill. The fourth product was full-length

Figure 42: Wood Harvested On-Site
Source: By Author, photographs courtesy of the Aldo Leopold Foundation

trees to be used for the small diameter, whole-log constructed roof trusses. They were sorted by species and into sawlogs, bolts and pulp. The sawlogs and the straight bolts were taken to Samsel's Sawmill in Hancock, WI for processing.

In addition to pines used for the building structure, pines and mixed hardwoods were used for siding, flooring, doors, some of the windows and furniture. The total harvest was over 100,000 kg, but only the 22,550 kg of Leopold Pines used as structural timber is considered in this research. In addition to the Leopold pines, the wood structure includes 16,418 kg of purchased framing lumber and 20,398 kg of OSB board. The embodied energy and carbon dioxide emissions for purchased wood structural components were taken from the ICE data base (Hammond, 2007).

Figure 43: Processing wood harvested on site compared to purchased structural wood
Source: By Author

5.3.2 Embodied Energy of Leopold Harvest & Purchased Wood

For the Leopold pines, each step from harvest in the forest to trimming was considered separately. For each piece of equipment used, the number of hours used and average energy consumption per hour was estimated. Based on interviews with Steve Swenson and data on the equipment, Figure 43 presents the embodied energy and carbon emissions for the Leopold Pine poles and timbers with the values for purchased framing lumber and OSB board. The values for site processing timber are considerably less than the values for framing lumber from the ICE database, roughly 20% of the embodied energy and carbon emissions compared to the framing lumber. The timber for the Aldo Leopold Foundation building was not kiln-dried. Peeled logs used as roof rafters and roof trusses required very little processing energy, just trimming and detailing

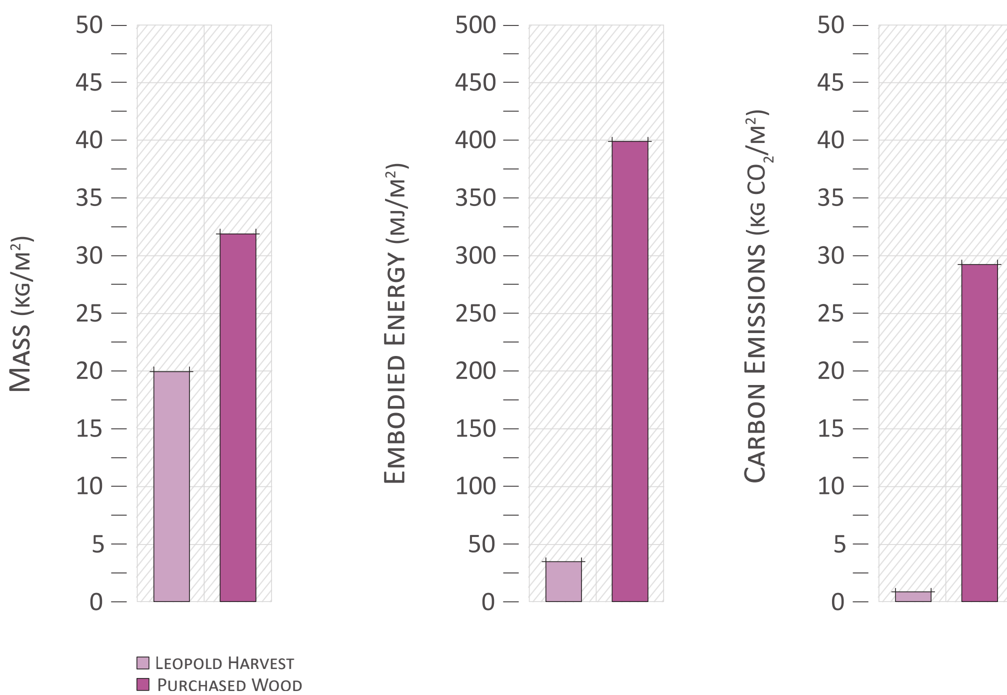


Figure 44: Leopold Harvest and Purchased Wood Comparison
Source: By Author

the ends. Timber columns and beams required four side squaring cuts and two end cuts. These processes explain some, but probably not all of the reductions compared with the ICE database.

For wood, the mass, embodied energy and CO_2 emissions per gross floor area are 53 kg/m^2, 428 MJ/m^2 and 30 kg CO_2/m^2 (Figure 44). The Leopold Pine timbers are 38.0% of the wood mass, 7.0% of the wood embodied energy and 7.4% of the wood CO_2 emissions. Figure 45 shows the variability in available wood data over the past 40 years. Indicated on the chart are the values of the embodied energy of the purchased wood for the Leopold foundation based on ICE coefficients, and the locally harvested Leopold pine completed in this study.

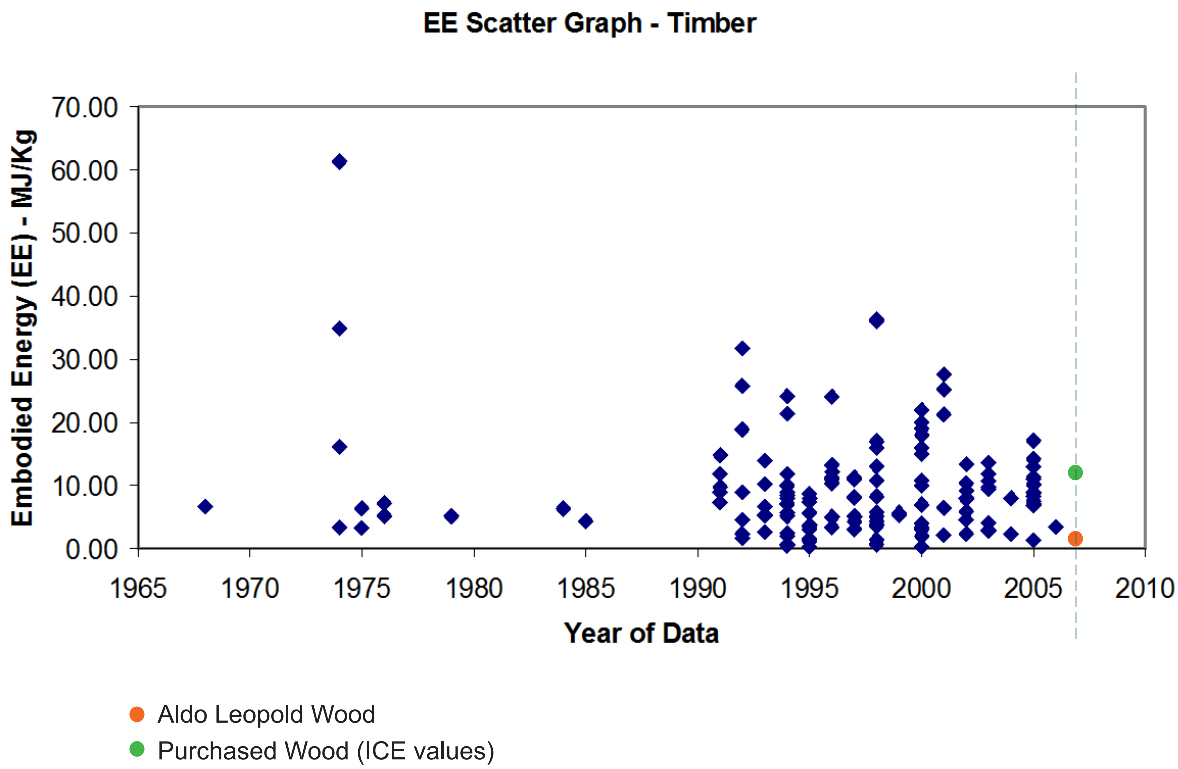


Figure 45: EE Scatter Graph
Source: Hammond & Jones, 2011. Leopold and Purchased Wood values by Author

5.3.3 Carbon Sequestered in Leopold Pine Forest

Carbon sequestration is discussed when assessing naturally grown materials, such as timber. When a tree grows it absorbs carbon dioxide from the atmosphere (through photosynthesis) and stores the carbon within the make up of the tree. Wood is roughly 50% carbon by dry weight.

To produce 1 kg cellulose, 0.55 kg H_2O + 1.63 kg of CO_2 are consumed (sequestered) and 1.18 kg of O_2 are emitted.

$$\underset{\text{from atmosphere}}{6CO_2} + \underset{\text{from soil}}{5H_2O} \xrightarrow{\text{photosynthesis}} \underset{\text{cellulose (sequestered)}}{C_6H_{10}O_5} + \underset{\text{to atmosphere}}{6O_2}$$

Carbon sequestered in Biomass of Managed Forests

Assumed sequestration rate:

0.18 kg Carbon per m^2 per year for Pine Forest

	Area	CO_2 Emissions (Metric Tons)
Leopold Pines	3.64 Hectares	-24.04 t CO_2

Source: Utzinger, 2012

CO_2 sequestered by Leopold Pine per year:
-24.04 metric tons x 1,000 kg CO_2 / (ALF area)1,106 m^2 = **-21.7 kg CO_2/m^2**

Figure 46: Carbon Sequestration in Leopold Forest per building area
Source: By Author

This could be claimed as biogenic carbon storage in an embodied carbon assessment, which is in essence a carbon benefit to the results (circularecology.com). It is important to acknowledge that at the end of life of such materials the stored carbon may be released back into the atmosphere, for example through incineration or through decaying in a landfill. Wood is carbon negative as a result of carbon sequestration, or in other words "storage". One kilogram of wood requires 1.63 kg of carbon dioxide on average and releases 1.11 kg of oxygen. Using wood from sustainably managed forests increases CO_2 removal from the atmosphere.

To get a holistic calculation of carbon emissions of the wood structure in the Aldo Leopold

Foundation building, carbon sequestration of the Leopold forest was considered. The sequestered carbon of the Leopold forest per building area amounts to -21.7 kg CO_2/m^2. The graphs on the left that the carbon sequestration is about -55 $kgCO_2/m^2$ for purchased wood (larger mass), and -25 $kgCO_2/m^2$ for the Leopold pine (Figure 47).

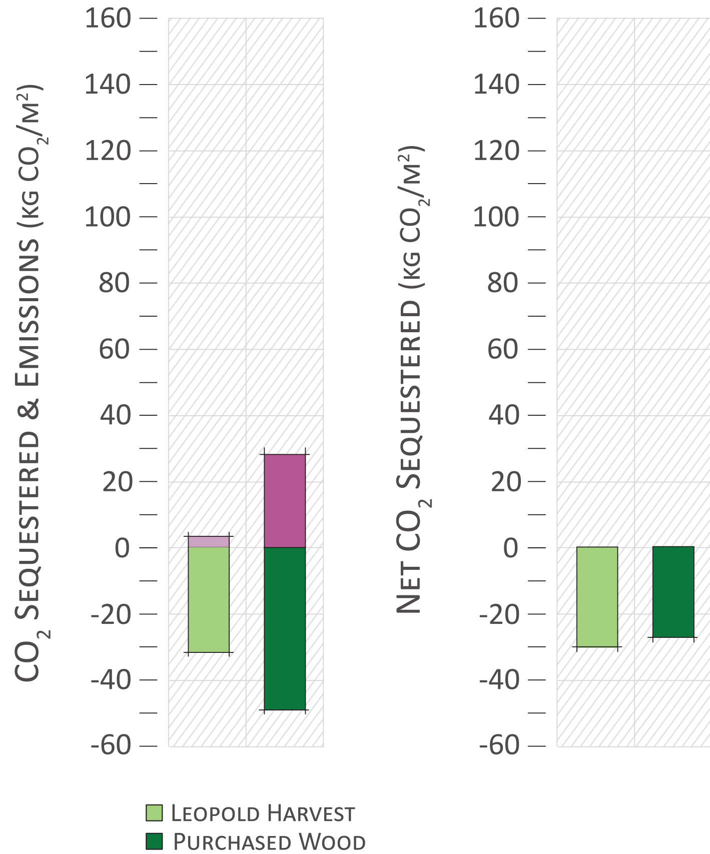


Figure 47: Carbon Sequestration Comparison
Source: By Author

5.4 Steel

Designers and builders choose steel as a building material for its strength, durability, and functionality. There is a strong economic value to incorporate recycling into the steel manufacturing process. Another value to recycling steel is its environmental attributes, particularly its high recycled content and high recovery rate. Recycled content is a measure of how much recycled material is contained in a finished product. The efficiency in which a material is recycled is indicated by its recovery rate, which is a measure of how often a product is recycled at the end of its useful life. Steel has a high recovery rate, meaning that it is a cradle-to-cradle material continuously multi-cycled into various forms of steel products. Steel scrap is re-melted and used to make new steel. In 2008, more than 475 million tonnes of steel scrap was diverted from the waste stream into the recycling stream (World Steel Association, 2009). This is more than the combined totals for other recyclable materials, including paper, plastic, glass, copper, lead, and aluminum (WBCSD, 2009). Steel recycling accounts for significant raw material and energy savings. Over 1,200 kg of iron ore, 7 kg of coal, and 51 kg of limestone are saved for one tonne of steel scrap used, making for significant reduction of CO_2 emissions. If 450 million tonnes of hot rolled steel were produced from 100% scrap rather then new materials, the total CO_2 savings would be approximately 811 million tonnes in one year (Brimacombe, et al., 2005).

Increased interest in recycling in the construction industry has been primarily driven by environmental assessment tools such as the LEED rating system, which provide credit for the use of materials with high levels of recycled content. In the Aldo Leopold Legacy Center, steel is used for concrete reinforcement and timber fasteners. LEED documents indicate that the reinforcing steel is 100% recycled; 97% was post-consumer while the remaining 3% was post-industrial.

The steel fasteners are 92% recycled; 59% was post-consumer and 33% was post-industrial (See Appendix A). The embodied energy of the steel in the Leopold Legacy Center was calculated based on energy coefficients provided in the ICE database (Hammond et al., 2011). These coefficients are specific to recycled content, therefore knowledge of the recycled content of the steel in the building allowed for accurate embodied energy calculations. Moreover, in order to calculate the embodied energy of the steel, the volume of the steel in the ALF is needed. The steel volumes were determined from the BIM model and the construction documents for the building. The BIM model which was previously created as part of the "Carbon Neutral Design" (CND) Project (Boake et al., 2008), included detailed modeling of the steel fasteners (Figure 48). The total steel fasteners, bolts

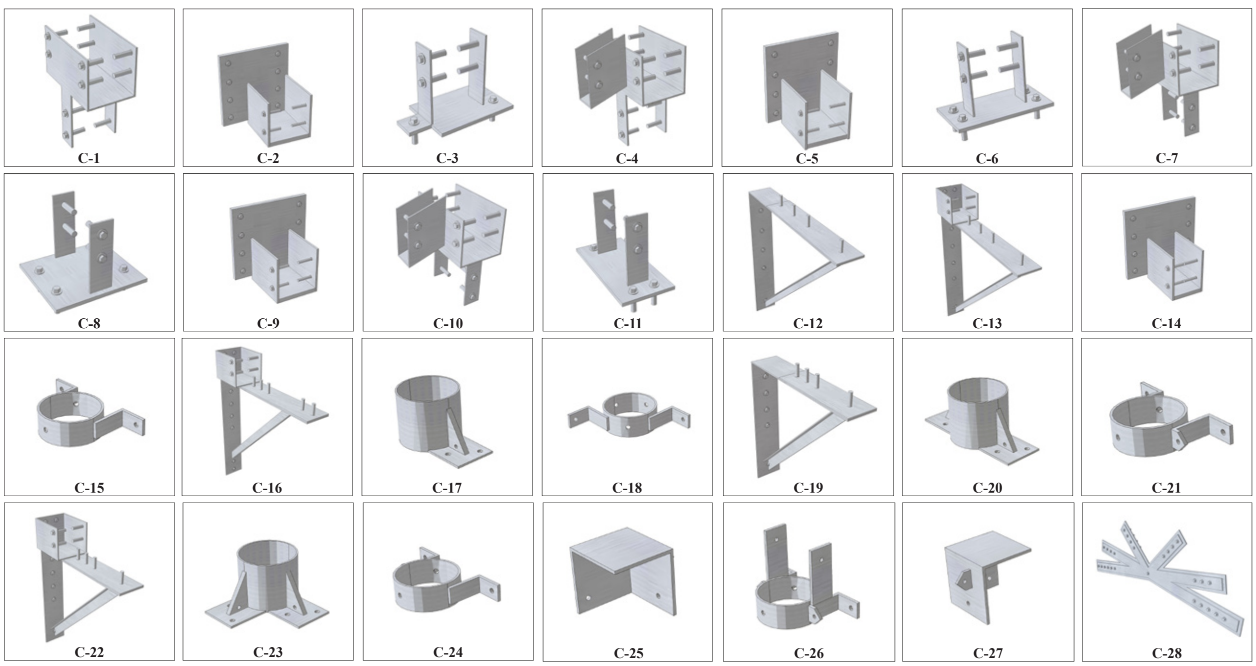


Figure 48: Various Steel Fasteners used in the ALF Building
Source: By Author, Obtained from ALF BIM Model

Figure 49: Examples of Various Steel Fasteners in the ALF Building
Source: Courtesy of Michael Utzinger

Steel Fasteners	Quantity	Volume (CF)
C-1	3	0.155
C-2	11	0.741
C-3	12	0.808
C-4	3	0.202
C-5	3	0.433
C-6	1	0.142
C-7	2	0.094
C-8	6	0.253
C-9	7	0.239
C-10	16	0.606
C-11	1	0.146
C-12	7	0.781
C-13	7	0.781
C-14	7	0.600
C-15	21	1.864
C-16	16	1.420
C-17	1	0.106
C-18	2	0.053
C-19	2	0.053
C-20	2	0.054
C-21	3	0.049
C-22	2	0.032
C-23	2	0.052
C-24	3	0.051
C-25	1	0.039
C-26	4	0.104
C-27	1	0.039
C-28	8	1.000
	Total	10.897

Steel Bolts	Quantity	Volume (CF)
B-1	3	0.035
B-2	11	0.169
B-3	12	0.185
B-4	3	0.046
B-5	3	0.014
B-6	1	0.005
B-7	2	0.015
B-8	6	0.046
B-9	7	0.047
B-10	16	0.123
B-11	1	0.005
B-12	7	0.061
B-13	7	0.114
B-14	7	0.128
B-15	21	0.182
B-16	16	0.262
B-17	1	0.006
B-18	8	1.136
	Total	2.579

Steel Tension Bars	Quantity	Volume (CF)
TB-1	6	0.074
TB-2	2	0.029
TB-3	8	0.141
	Total	0.244

Table 06: Volumes of Steel Fasteners, Bolts, and Tension Bars
Source: By Author, Obtained from ALF BIM Model

and tensions bars sums to 13.72 cf (0.389 m^3) (Table 06).

The steel reinforcement volume was obtained by extracting information from the building's construction documents and incorporating this information in 3-dimenional form in the BIM model (Figure 50). The sum of steel reinforcement, manufactured by Gerdau Ameristeel, amounted to 29.24 cf (0.828 m^3). Transportation distance was determined from the manufacturer's location (see Appendix B), truck fuel efficiency was assumed to be 0.73 MJ per kg material per 1,000 km.

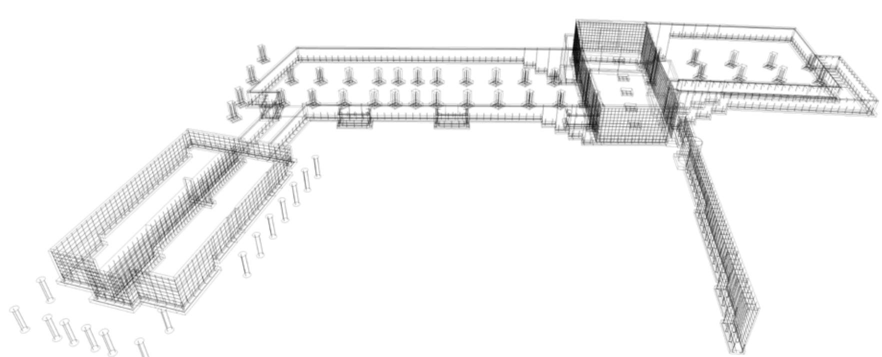


Figure 50: Steel Reinforcement
Source: By Author

For the steel fasteners and reinforcing rods, the mass, embodied energy and CO_2 emissions per gross floor area are: 8.4 kg/m^2, 84.6 MJ/m^2 and 4.5 kg CO_2/m^2. The reinforcing rods are 69.7% of the steel mass, 62.6% of the steel embodied energy and 60.6% of the steel CO_2 emissions. (See Appendix B). If the steel connectors and reinforcing were assumed to have an average recycled content of 59%, the total steel embodied energy content would increase by 83 MJ/m^2 and carbon dioxide emissions by 5.6 kg CO_2/m^2. Figure 51 compares the embodied energy and carbon emissions

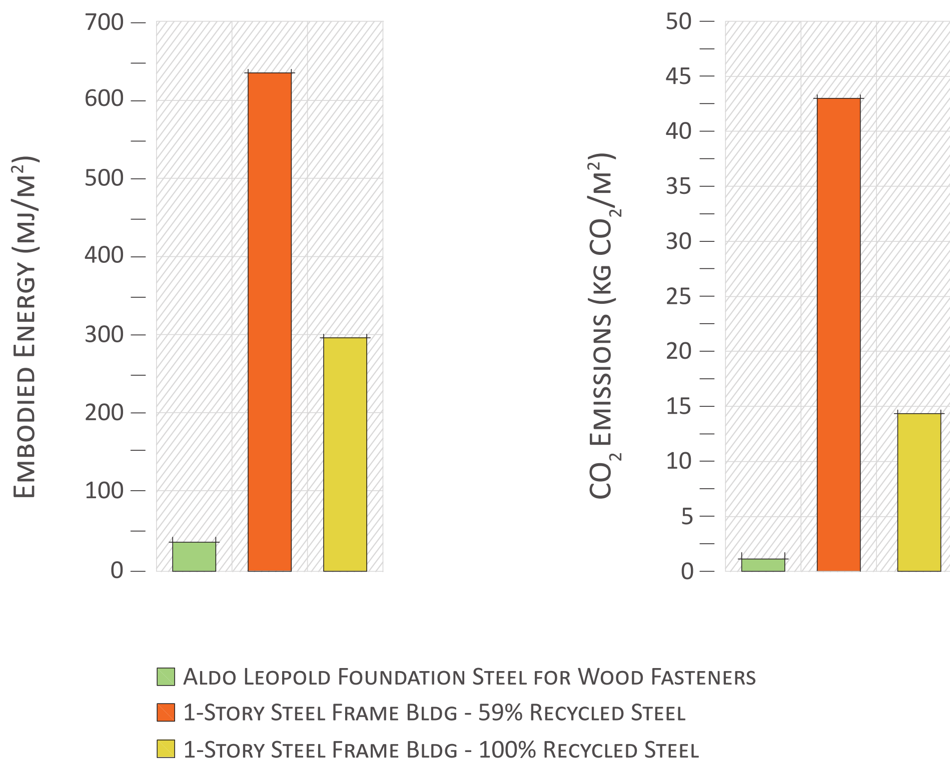


Figure 51: Steel EE and CE Comparison
Source: By Author

of the steel used in the Aldo Leopold Center, a 1-storey steel frame building with the same area as the ALF building and 59% recycled steel, and a 1-storey steel frame building with 100% recycled steel. This comparison shows that the timber structure of the ALF saved 86% embodied energy and 88% carbon emissions respectively, in comparison to it being a typical all steel frame structure with 59% recycled steel content.

5.5 Masonry

The building site sits on a gentle north-facing slope of deep sandy soil. To create the flat outdoor work yard, formal garden and entry to the basement mechanical room, approximately 300 meters of retaining walls were required. The retaining walls ranged from 1 meter to 3 meters in height. The volume and height of the walls was determined from the BIM model and verified in a site visit. The original design called for concrete retaining walls on the site. During construction,

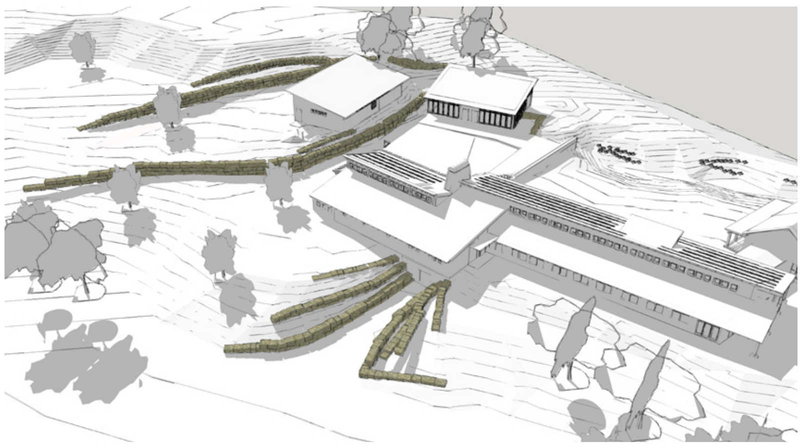


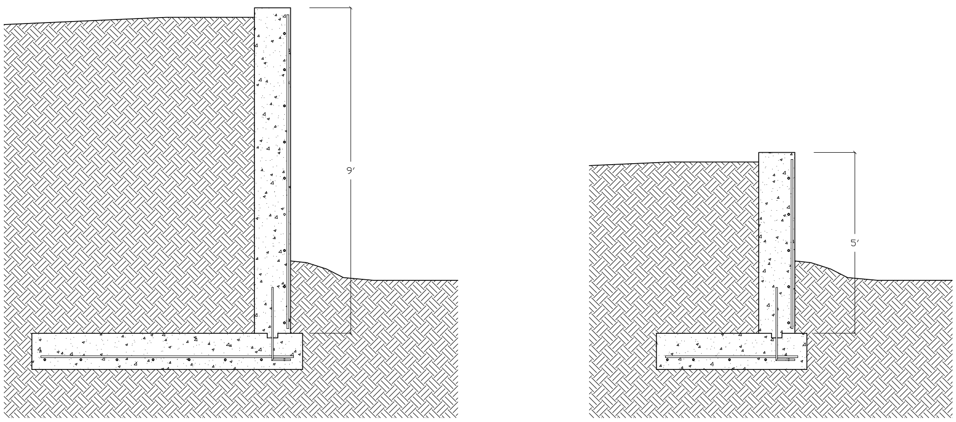
Figure 52: Rendering of ALF Highlighting Masonry Retaining Walls
Source: By Author, Based on BIM Model

Figure 53: Retaining Walls During Construction
Source: Courtesy of Michael Utzinger, 2006

Figure 54: Masonry Retaining Walls
Source: Courtesy of Michael Utzinger

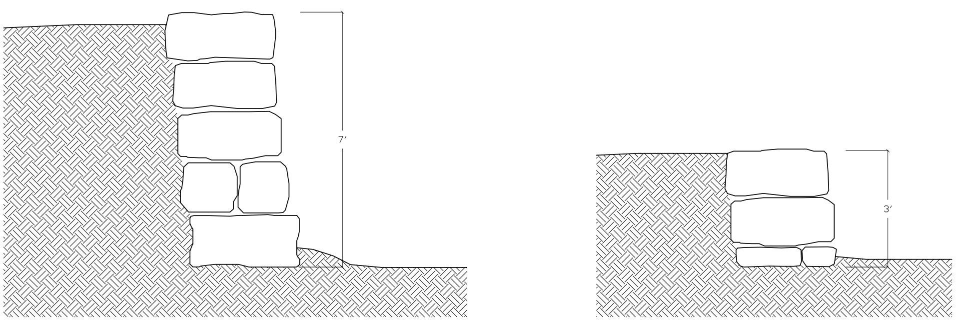
the site excavator suggested using stone instead of concrete. The excavator knew a source of stone available from a nearby quarry. As the construction process was design build, deciding to change materials for the retaining walls was relatively simple, providing a substantial savings over reinforced concrete retaining walls. The stone had been previously quarried. Energy and emissions were limited to loading, transporting and placing the stone. The loading and placing

costs were estimated to be three times greater than the transportation costs. For stone retaining walls, the mass, embodied energy and CO_2 emissions per gross floor area are: 659 kg/m^2, 52 MJ/m^2 and 4 kg CO_2/m^2. As originally designed, the reinforced concrete retaining wall would have required a concrete mass of 760 kg/m^2, 76% of the concrete used for footings, foundation walls and slabs. The embodied energy of the concrete retaining walls is 554 MJ/m^2 greater than the embodied



EE: 16.08 MJ/kg
CE: 1.50 kg CO_2/kg

Figure 55: Concrete Retaining Walls
Source: By Author



EE: 0.06 MJ/kg
CE: 0.01 kg CO_2/kg

Figure 56: Stone Retaining Walls
Source: By Author

energy of the stone retaining wall and results in 72.5 kg CO_2/m^2 greater emissions. Stone is a building material in which architects have control of when specifying materials for a project, and provides significant environmental savings over alternative materials such as reinforced concrete. Figure 57 shows a comparison of the embodied energy and carbon emissions of the stone retaining wall, versus concrete walls as originally planned in the design.

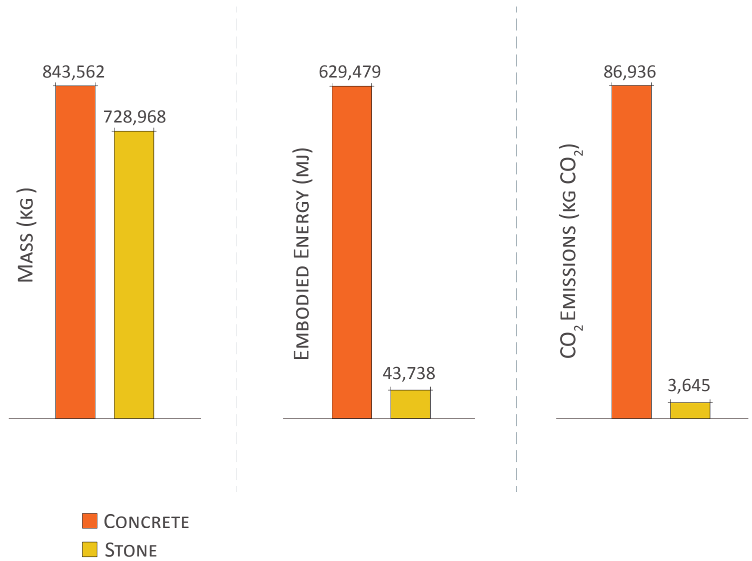


Figure 57: EE & CE of Stone compared to concrete Retaining Walls
Source: By Author

5.6 Photovoltaic Panels

Photovoltaic energy conversion is a renewable energy technology that has the potential to positively contribute to a sustainable energy supply and mitigate greenhouse gas emissions. In order to fulfill these promises photovoltaic (PV) technology has to meet two requirements: 1) PV energy generation should have an acceptable cost/performance ratio and 2) the net energy yield for PV systems should be larger than zero. With a positive energy yield we mean that the energy output during the lifetime of the PV system must be larger than the energy inputs during the system's life cycle, i.e. for manufacturing of the components and for the installation, maintenance and decommissioning of the PV system. Of course evaluations of the CO_2 mitigation potential of PV technology should be based on expected net energy yields. In practice this is seldom done, leading to over-optimistic results for the CO_2 mitigation potential.

In every new energy technology which is promoted as being "renewable" or "sustainable" should be subjected to an analysis of its energy balance in order to calculate the net energy yield. Of great importance is that such an energy analysis is not only based on data for present-generation

systems but also considers expected improvements in production and energy system technology. Since energy consumption generally has significant environmental implications, the energy analysis may be considered as a first step towards a more comprehensive environmental Life Cycle Assessment (Nieuwlaar and Alsema, 1998). Furthermore energy analysis results provide a good indication of the CO_2 mitigation potential of the considered energy technology. The intention is to provide estimates of the energy requirements for manufacturing of PV systems and to evaluate the energy balance for a few representative examples of PV system applications.

A 39.4 kW roof mounted PV array provides 70% of the annual building energy consumption. The array contains 198 Kyocera KC200GT poly-Si panels rated ate 14.2% efficiency with a measured annual system efficiency of 10.4%. The estimated embodied energy of the system is 934 MJ/m^2 of building area based on similar PV systems (Fthenakis, 2011). The panels were manufactured in Arizona. Using the grid based CO_2 emissions per kWh (Deru and Torcellini, 2007), the CO_2 emissions of the array manufacture per unit floor area of the building are 142.5 kg CO_2 (Figure 58). This is compared with the embodied energy of the structural materials in section 5.7.

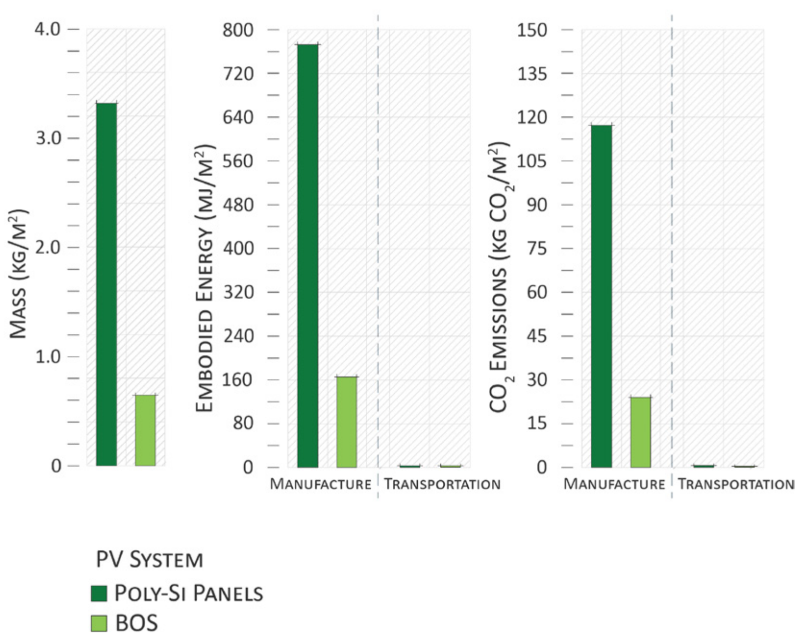


Figure 58: EE & CE of the Photovoltaic System
Source: Utzinger and Qarout, 2015

5.7 Results

The structural material mass, embodied energy and carbon dioxide emissions are illustrated per unit building floor area in Figure 59. Embodied energy and CO_2 emissions are divided into manufacturing and transportation components. In addition structural materials are divided where appropriate. Cement is less than 10% of the concrete mass while accounting for more than 70% of the embodied energy and more that 85% of the carbon dioxide emissions. Transportation of materials to the building site accounts for only 13% of the embodied energy and 10% of the carbon dioxide emissions. The total embodied energy of the structure is 18% greater than the PV system while the CO_2 emissions of the structure are 7.4% less than the CO_2 emissions of the PV system.

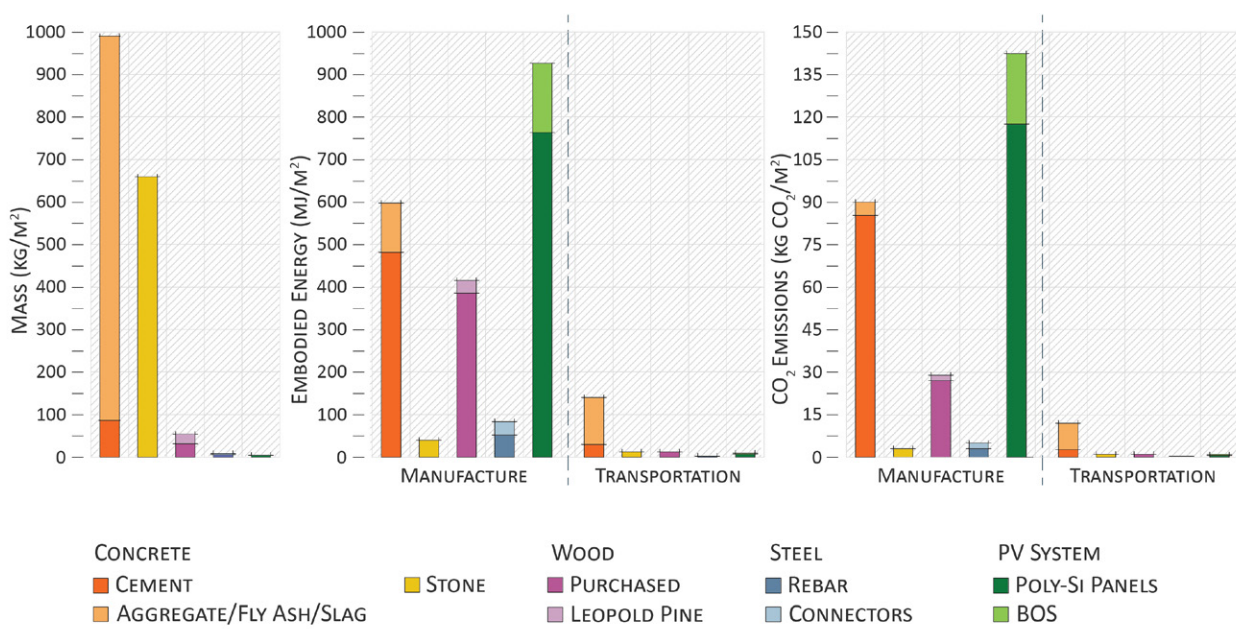


Figure 59: Structure material mass, embodied energy and carbon dioxide emissions per unit building floor area.
Source: By Author

5.7.1 Avoided embodied energy and emissions

If fly ash and slag were not included in the concrete mix and the cement content increased accordingly, the concrete embodied energy would increase by 226 MJ/m^2 and the carbon dioxide

emissions by 44.3 kg CO_2/m^2. Substituting fly ash and slag for a portion of the cement generates significant savings, 17.4% of the total embodied energy and 31.4% of the total carbon dioxide emissions. Steel typically has a reasonable percentage of recycled post industrial and post consumer content. If the steel connectors and reinforcing were assumed to have an average recycled content of 59%, the total steel embodied energy content would increase by 83 MJ/m^2 and carbon dioxide emissions by 5.6 kg CO_2/m^2.

The building site sits on a gentle north-facing slope of deep sandy soil. To create the flat outdoor work yard, formal garden and entry to the basement mechanical room, roughly 300 meters of retaining walls were required. The retaining walls ranged from 1 meter to 3 meters in height. As originally designed, the reinforced concrete retaining wall would have required a concrete mass of 760 kg/m^2, 76% of the concrete used for footings, foundation walls and slabs. The embodied energy of the concrete retaining walls is 554 MJ/m^2 greater than the embodied energy of the stone retaining wall and results in 72.5 kg CO_2/m^2 greater emissions.

To estimate the impact due to use of the Leopold Pines, the pine timber was assumed replaced by timbers from the west cost. The increased embodied energy is 131 MJ/m^2 and the additional emissions are 10.6 kg CO_2/m^2. The total avoided embodied energy and carbon emissions for all four materials is 994 MJ/m^2 and 133.0 kg CO_2/m^2 respectively. These totals are on the same order of magnitude as the totals for all structural materials included in the building: 1,302 MJ/m^2 and 141 kg CO_2/m^2. The building structure system is typically custom designed. Structural systems offer the design teams a great opportunity to reduce embodied energy and CO_2 emissions. For the Aldo Leopold Legacy Center, the reduction is roughly 50% (43% of the embodied energy and 48% of the CO_2 emissions). Over half the avoided energy and CO_2 emissions is due to the replacement of concrete retaining walls with stone retaining walls.

These results highlight the discrepancies between a detailed analysis and available embodied energy assessment tools. Building Information Modeling tools that seek to quantify embodied energy along with other environmental impacts and emissions give a rough estimation based on material quantity in the model. Kieran Timberlake's Tally – a plug-in for Revit, does not allow the input of material transportation, or specific recycled content for example. Figure 60 shows the variation in output between Tally results and the calculations in my research that are based on detailed assessment for the concrete used in the construction of the Aldo Leopold Foundation.

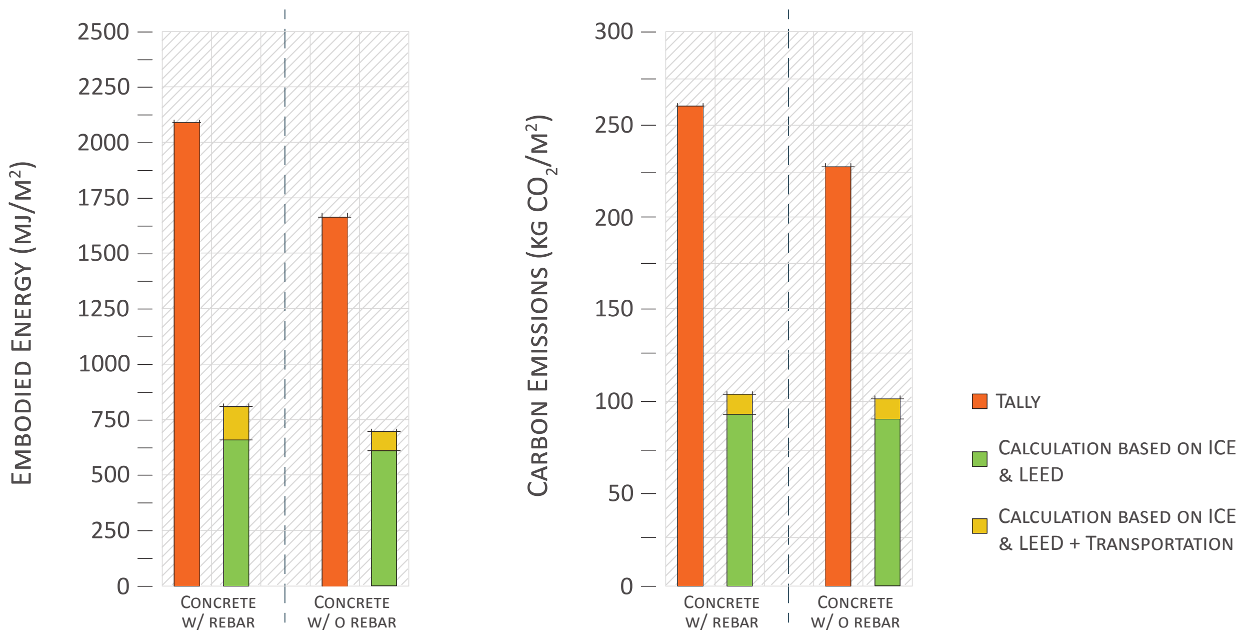


Table 60: Comparison between Results in This Study & Tally Results for Concrete
Source: By Author

6 Conclusion

6.1 Construction to Operational Energy Comparison

The 1,106 m^2 Aldo Leopold Legacy Center is an all-electric building using radiant slabs for thermal comfort with slab temperatures maintained by a ground source heat pump system. A 39.4 kW dc peak PV array provides solar generated electricity on site. Energy consumed for heating, cooling and ventilation as well as lighting, appliances, and hot water was determined based on seven years of energy bills for the Aldo Leopold Foundation (Table 07). The measured average annual energy utilization intensity (EUI) and resulting annual operational CO_2 emissions are compared with the structure system embodied energy and CO_2 emissions in Figure xx.

	Estimated Solar Used Directly	Estimated Total Use				
Year	Annual	Annual	EUI	Renewable EUI	Net Grid EUI	Biofuels
2008	23,733 kWh	73,093 kWh	20.96 kBtu/SF/yr	13.77 kBtu/SF/yr	7.20 kBtu/SF/yr	
2009	20,194 kWh	61,394 kWh	17.61 kBtu/SF/yr	13.77 kBtu/SF/yr	3.84 kBtu/SF/yr	
2010	20,030 kWh	65,430 kWh	18.77 kBtu/SF/yr	13.77 kBtu/SF/yr	5.00 kBtu/SF/yr	
2011	24,669 kWh	75,069 kWh	21.53 kBtu/SF/yr	13.77 kBtu/SF/yr	7.76 kBtu/SF/yr	
2012	19,788 kWh	63,028 kWh	18.08 kBtu/SF/yr	13.77 kBtu/SF/yr	4.31 kBtu/SF/yr	
2013	25,587 kWh	81,827 kWh	23.47 kBtu/SF/yr	13.77 kBtu/SF/yr	9.70 kBtu/SF/yr	
2014	28,906 kWh	94,066 kWh	26.98 kBtu/SF/yr	13.77 kBtu/SF/yr	13.21 kBtu/SF/yr	
			21.06 kBtu/SF/yr	13.77 kBtu/SF/yr	7.29 kBtu/SF/yr	13.56 kBtu/m^2/yr
			253 MJ/(m^2*yr)	156 MJ/(m^2*yr)	83 MJ/(m^2*yr)	14 MJ/(m^2*yr)
Average energy use for the past 7 years			70 kWh/(m^2*yr)	43 kWh/(m^2*yr)	23 kWh/(m^2*yr)	4 kWh/(m^2*yr)
			18.2 kg CO2e/m^2	0.0 kg CO2e/m^2	17.1 kg CO2e/m^2	1.1 kg CO2e/m^2

Table 07: Average ALF Energy Use Over a Period of 7 years
Source: Utzinger, 2015

With a measured EUI of 253 MJ/m^2 per year of which only 83 MJ/m^2 per year is from fossil fuel generated electricity, the Aldo Leopold Legacy Center is among the highest performing buildings built prior to 2010. Annual carbon emissions are 18.2 kg CO_2/m^2 per year (17.1 from fossil fuel combustion). The embodied energy of the structural system is roughly five times greater than the annual EUI of the building (Figure 61). Stated another way, five years of operation EUI is roughly equal to the embodied energy of the structure system. Carbon emissions of the structure

system are eight times larger that annual operational carbon emissions (Utzinger & Qarout, 2015).

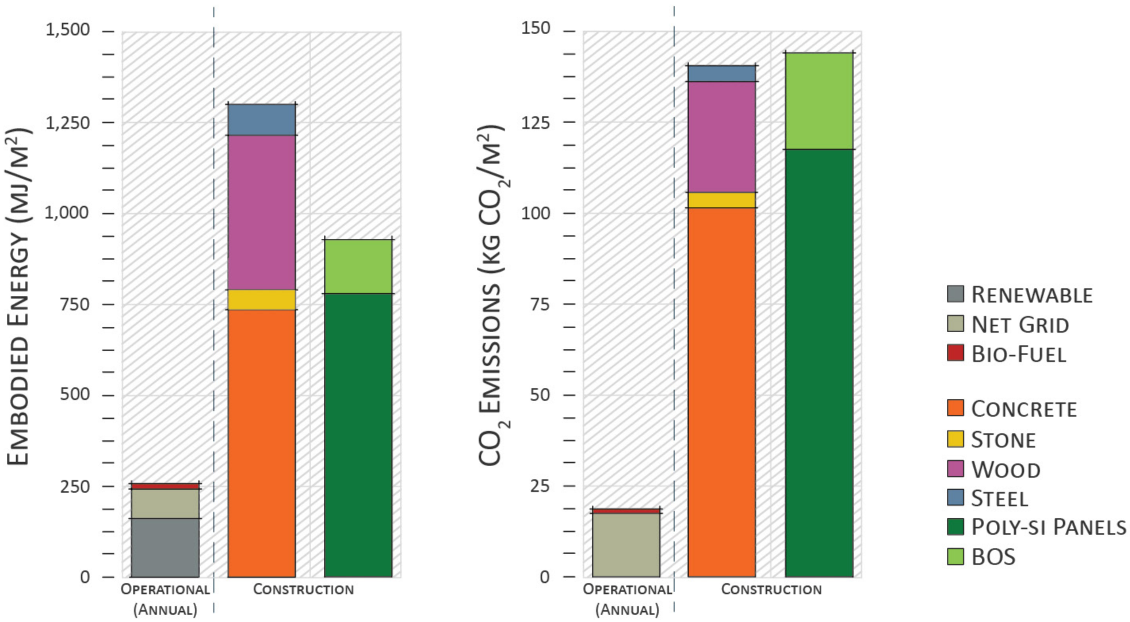


Figure 61: EUI & Annual CO_2 vs. Construction EE & CO_2
Source: Utzinger & Qarout, 2015

6.2 Discussion of Results

6.2.1 Building Cost

The greatest opportunities to reduce EE and CO_2 emissions occur when one material is replaced with a more ecological material. Replacing concrete retaining walls with stone had the largest impact reducing EE and CO_2 emissions in this project. This change resulted in a savings of over \$110,000 (\$10/m^2) (Utzinger & Qarout, 2015). However, dollars flowing to the local labor pool were reduced with this change. Working directly with wood harvested from a local forest is unusual, but not unique. Using locally sourced wood did reduce EE (10%) and CO_2 emissions (7.5%). The wood harvest was certified as sustainably managed. The total certified harvest was valued at \$269,000 (\$55,000 for the Leopold Pine structural timber). The cost of harvesting and milling the structural lumber was \$9,400 giving a net value for the locally harvested structural

wood of $45,600 (Utzinger & Qarout, 2015). The construction cost of the Aldo Leopold Legacy Center was $3,655 per m^2. The cost of constructing the structure was $1,122 per m^2 including $618 per m^2 for labor. The building is expensive, typical construction costs for this quality building would be $2,400 per m^2. However, this building met the owner's expectation for a building that would be ecologically sensitive and would use would culled from the Leopold forests to improve forest health. As the labor was local and fundraising for the project was national, the building provided a boost to the local economy.

6.2.2 Embodied Energy Savings

Steel typically has a reasonable percentage of recycled post industrial and post consumer content. If the steel connectors were to have a typical average recycled content of 59%, the total steel embodied energy content would increase by 8 MJ/m^2 (Figure xx). Choosing locally sourced and processed materials, which offer an opportunity to substantially reduce embodied energy and CO_2 emissions. The owner's decision to locally harvest the timber for the building's structure saved 122 MJ/m^2 in embodied energy, and 10 kg CO_2/m^2.

If fly ash and slag were not included in the concrete mix and the cement content increased accordingly, the concrete embodied energy would increase by 226 MJ/m^2 and the carbon dioxide emissions by 44.3 kg CO_2/m^2. Substituting fly ash and slag for a portion of the cement generates significant savings, 17.4% of the total embodied energy and 31.4% of the total carbon dioxide emissions. As originally designed, the reinforced concrete retaining wall would have required a concrete mass of 760 kg/m^2, 76% of the concrete used for footings, foundation walls and slabs. The embodied energy of the concrete retaining walls is 554 MJ/m^2 greater than the embodied energy of the stone retaining walls, and results in 72.5 kg CO_2/m^2 greater emissions.

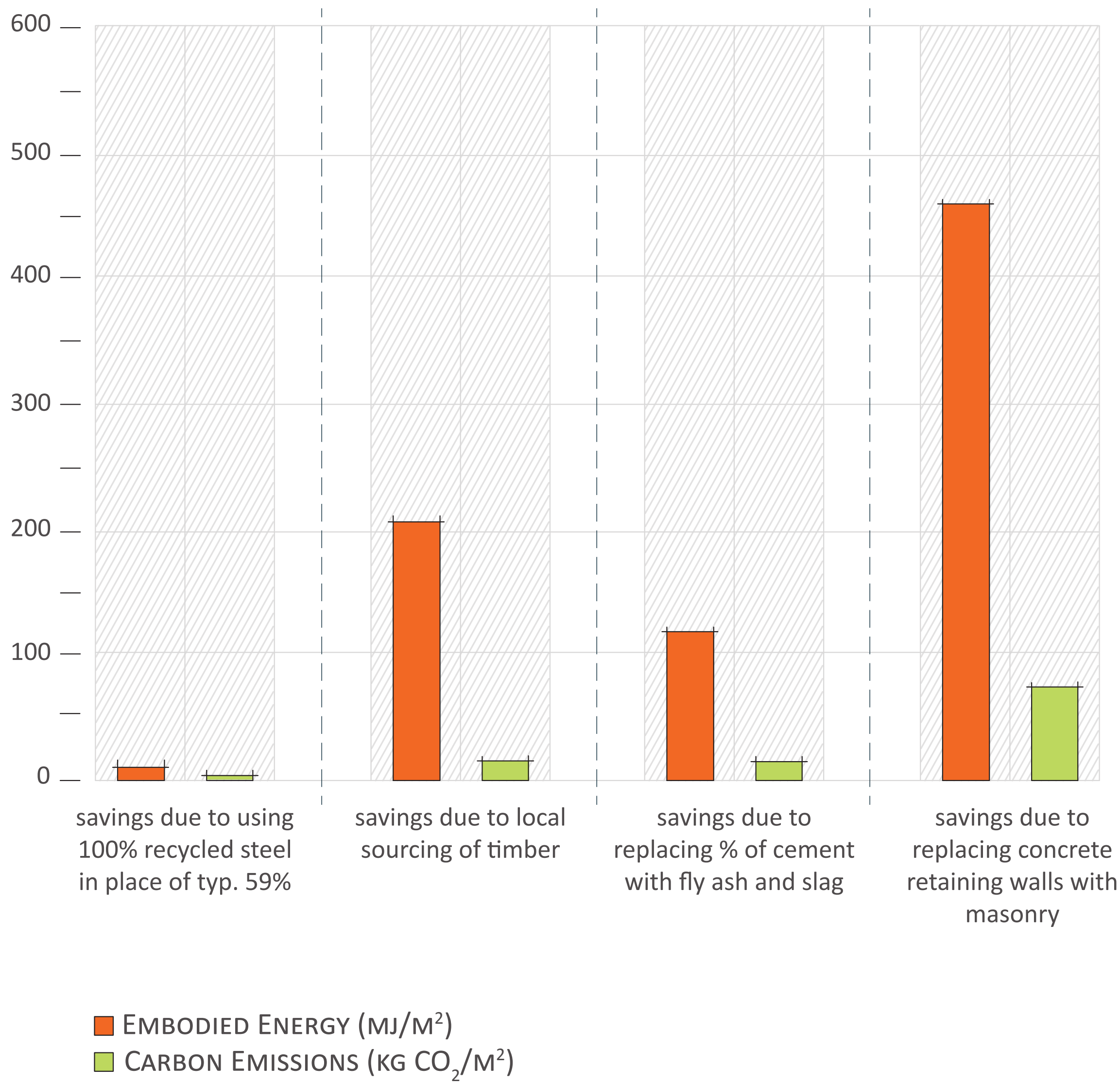


Figure 62: Embodied Energy and Carbon Savings
Source: By Author

As mentioned above, the Aldo Leopold Foundation is an all-electric building using radiant slabs for thermal comfort with slab temperatures maintained by a ground source heat pump system. Energy consumed for heating, cooling and ventilation as well as lighting, appliances, and hot water was determined based on seven years of energy bills for the Aldo Leopold Foundation. With a measured EUI of 253 MJ/m^2 per year of which only 83 MJ/m^2 per year is from fossil fuel generated electricity, the Aldo Leopold Legacy Center is among the highest performing buildings built prior to 2010. Annual carbon emissions are 18.2 kg CO_2/m^2 per year. The embodied energy

of the structural system is about five times greater than the annual EUI of the building. Meaning, five years of operation EUI is roughly equal to the embodied energy of the structure system.

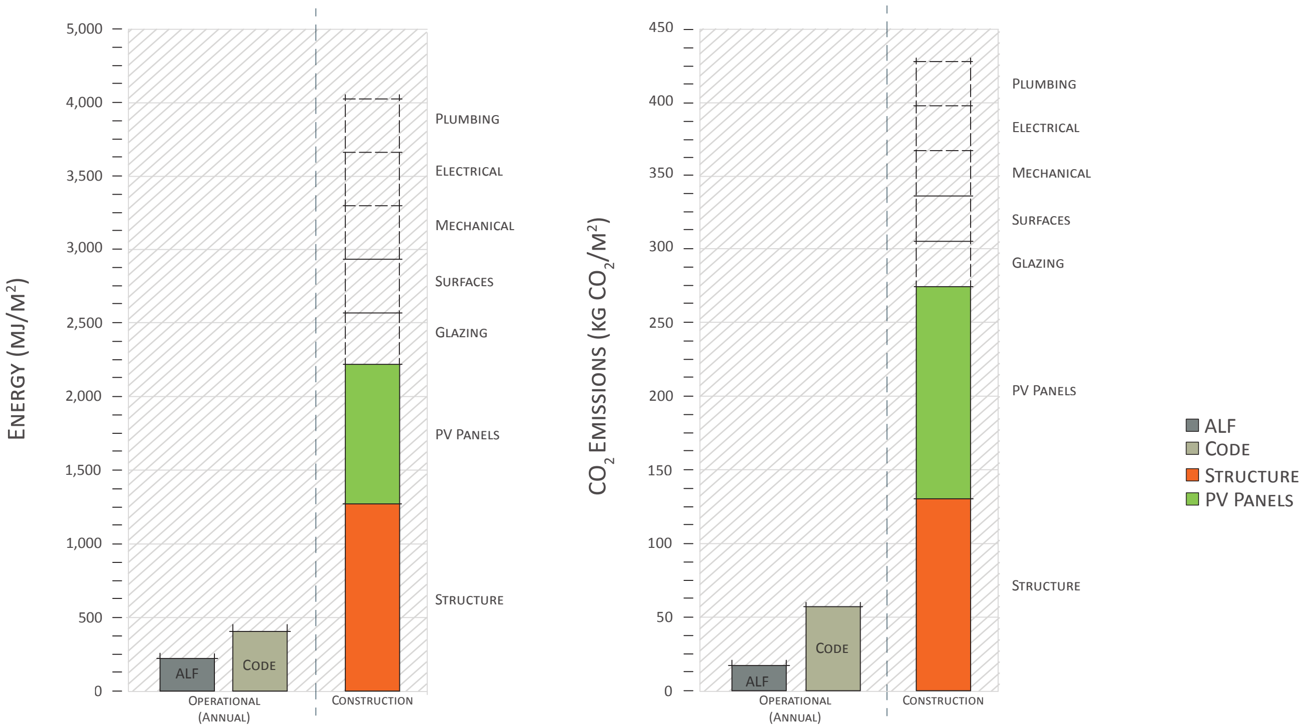


Figure 63: Embodied Energy Compared to Operational Energy (annual)
Source: Utzinger & Qarout, 2015

Carbon emissions of the structure system are eight times larger than annual operational carbon emissions. This means that the embodied energy and CO_2 emissions due to construction in a high-performance buildings are a major part of the 100-year life of the building, almost the same as that of operation (Figure xx). The embodied energy of the PV panels is equal to the 100-year net grid operational energy. Yet the PV panels require replacement at an average of 25 years. Considering the replacement of the PV panels over a 100-year life cycle, the system's embodied energy becomes equal to that of the net grid energy. However, over the 100-year life cycle of the Aldo Leopold Foundation building, the PV panels generate approximately 75% of the energy required for operation.

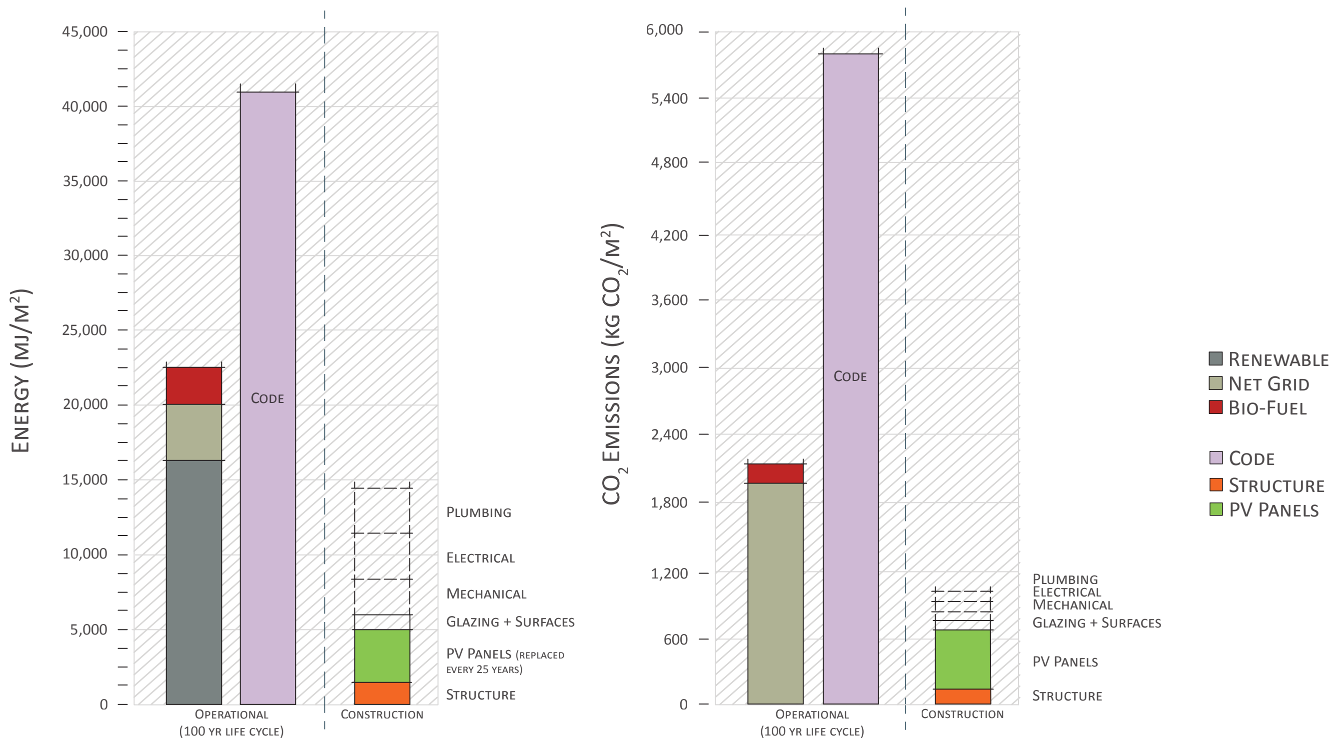


Figure 64: Embodied Energy Compared to Operational Energy (100 year life cycle)
Source: Utzinger & Qarout, 2015

6.3 Contribution & Future Research

Although the scope of the research did not include the construction phase or end of life phase energy, the study shows that a high performance building has an occupancy/use phase energy consumption that is at a similar order of magnitude with the building material production phase. The greatest opportunities to reduce EE and CO_2 emissions occur when one material is replaced with a more ecological material. Replacing concrete retaining walls with stone had the largest impact reducing EE and CO_2 emissions in this project. This change was a result of a design decision on site.

Working directly with wood harvested from a local forest is not typical, but not exceptional. Using locally sourced wood reduced EE and CO_2 emissions, a design decision made by the owner.

This research can begin to advance best practices in architectural design. Possibly implementing strategies, learning how to specify materials such as concrete for example, and the impact it has on the total life cycle energy of a building. Additionally, there is great potential to develop the excel spreadsheets and data generated for this research into an embodied energy assessment tool in the future.

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Appendix A
LEED Documentation

MR Credit 3 / MR Credit 4 / MR Credit 5 / MR Credit 6 / MR Credit 7 | **MR Credit 3 / MR Credit 4 / MR Credit 5 / MR Credit 6 / MR Credit 7**

Materials Table

	Description of Material			Total Construction Cost	Labor Cost	Equipment Cost	Material Cost (Less Labor & Equipment)	MR Credit 3: Resource Reuse	MR Credit 4: Recycled Content: Post-Consumer			MR Credit 5: Local/Regional Materials: Credit 5.1 Manufacture		MR Credit 6: Rapidly Renewable Materials	MR Credit 7: New Wood-Based Materials	
									Post-Consumer	Post-Industrial	Value	Credit 5.1 Manufacture	Credit 5.2 Harvested		New Wood-Based Materials	Certified Wood
				[$]	[$]	[$]	[$]	[$]	[%]	[%]	[$]	[$]	[$]	[$]	[$]	[$]
02	**SITEWORK**															
02200	Earthwork - S	Earthwork	LMS Construction	$112,415	$22,746	$81,306	$8,363	$0	0%	0%	$0	$8,363	$8,363	$0	$0	$0
02200	Install Earth Tubes - S	Install Earth Tubes 24381	LMS Construction	$24,381	$24,381	$0	$0	$0	0%	0%	$0	$0	$0	$0	$0	$0
02505	Gravel Parking Lots - S	Gravel Parking Lots	LMS Construction	$11,965	$1,148	$6,973	$3,845	$0	0%	0%	$0	$3,845	$3,845	$0	$0	$0
02505	Stone Paving - S	Stone Paving 30621	D.L. Gasser Construction	$30,621	$6,000	$6,021	$18,600	$0	0%	0%	$0	$18,600	$18,600	$0	$0	$0
03	**CONCRETE**															
03000	Ready-Mix - M	Ready-Mix 43000	Lycon Inc.	$43,000	$0	$0	$43,000	$0	0%	40%	$43,000	$43,000	$43,000	$0	$0	$0
03000	Concrete Rebar - M	Rebar 13000	Gerdau Ameristeel	$13,000	$0	$0	$13,000	$0	97%	3%	$64,025	$0	$0	$0	$0	$0
03000	Waterproofing - S	Waterproofing 3290	Zander Solutions LLC	$3,290	$2,232	$0	$1,058	$0	0%	0%	$0	$0	$0	$0	$0	$0
03000	Concrete - S	Concrete - FPF 252021	Middleton Construction	$252,021	$214,421	$15,000	$22,600	$0	0%	0%	$0	$0	$0	$0	$0	$0
03001	Stained Concrete Floors - S	Concrete Stain 13195	Artistic Concrete	$13,995	$8,919	$0	$5,076	$0	0%	0%	$0	$0	$0	$0	$0	$0
04	**MASONRY**															
04000	Earth Tubes - M	Earth Tubes - 2865.65	County Materials	$2,866	$0	$0	$2,866	$0	0%	18%	$1,290	$2,866	$2,866	$0	$0	$0
15500	Earth Tubes - M	Earth Tubes	County Materials	$11,971	$0	$0	$11,971	$0	0%	18%	$5,387	$11,971	$11,971	$0	$0	$0
15500	Earth Tubes - M	CMU	County Materials	$4,691	$0	$0	$4,691	$0	0%	30%	$3,518	$4,691	$4,691	$0	$0	$0
04000	Mortar-M	Masonry	Monona Masonry	$3,358	$0	$0	$3,358	$0	0%	33%	$2,770	$0	$0	$0	$0	$0
04000	Grout-M	Masonry	Monona Masonry	$1,015	$0	$0	$1,015	$0	0%	50%		$0	$0	$0	$0	$0
04000	Stone Caps-M	Masonry	Monona Masonry	$5,280	$0	$0	$5,280	$0	0%	0%	$0	$5,280	$5,280	$0	$0	$0
04000	Misc Metal Lintels/Ties/Reinforcment-M	Masonry	Monona Masonry	$4,914	$0	$0	$4,914	$0	59%	33%	$18,402	$0	$0	$0	$0	$0
04000	Masonry - S	Masonry - 136686.72	Monona Masonry, Inc.	$122,120	$104,213	$5,500	$12,407	$11,600	$0	$0	$0	$0	$0	$0	$0	$0
05	**METALS**															
05100	Misc. Steel - M	Misc. Steel 61712	Mid-City Steel Fab.	$61,712	$0	$0	$61,712	$0	59%	33%	$232,963	$61,712	$0	$0	$0	$0
06	**WOODS & PLASTICS**															
06000	Carpentry - M	Misc. Lumber 91879.11	Portage Lumber Co.	$77,458	$0	$0	$77,458	$0	0%	0%	$0	$0	$0	$0	$70,214	$0
06000	Hangers - M	Hangers	Portage Lumber Co.	$11,987	$0	$0	$11,987	$0	23%	7%	$15,972	$0	$0	$0	$0	$0
06000	Homasote - M	Homasote	Portage Lumber Co.	$2,434	$0	$0	$2,434	$0	98%	0%	$11,928	$0	$0	$0	$0	$0
06000	Gypsum Board - M	Gypsum Board	Portage Lumber Co.	$2,047	$0	$0	$2,047	$0	5%	37%	$2,380	$0	$0	$0	$0	$0
06000	Solid Wood Timbers - M	Solid Wood Timbers 2425.88	Glenville Timberwrig	$2,426	$0	$0	$2,426	$2,426	0%	0%	$0	$2,426	$0	$0	$2,426	$0
06000	Skyblend - M	Skyblend 2176	Certified Wood Products	$2,176	$0	$0	$2,176	$0	100%	0%	$10,880	$0	$0	$2,176	$0	$0
06000	FSC Certified Lumber - M	FSC Certified Lumber 19777.80	Certified Wood Products	$19,778	$0	$0	$19,778	$0	0%	0%	$0	$0	$0	$0	$19,778	$19,778
06000	Carpentry - S	Carpentry - 909274	Bachmann Construction	$909,274	$791,200	$62,240	$55,834	$0	0%	0%	$0	$0	$0	$0	$0	$0
06000	FSC Certified Wood - OWNER		Aldo Leopold Foundation	$0	$0	$0	$0	$0	0%	0%	$0	$238,489	$238,489	$0	$238,489	$238,489
06001	SIPS Panels - M	SIPS Panels - 76076.46	ACH Foam Technologies	$76,076	$0	$0	$76,076	$0	0%	0%	$0	$76,076	$0	$0	$0	$0
06272	Concrete Countertops - S	Concrete Countertops 6580	Decorative Concrete	$6,580	$4,189	$0	$2,391	$0	0%	0%	$0	$0	$0	$0	$0	$0
07	**THERMAL / MOISTURE PROTECTION**															
07220	Spray Insulation - S	Spray Insulation 16379	Rainbow Insulators	$16,379	$3,242	$0	$4,501	$0	0%	0%	$0	$0	$0	$0	$0	$0
07540	Spray Insulation - M	Cellulose Insulation-M	Rainbow Insulators	$0	$0	$0	$8,636	$0	60%	40%	$34,544	$8,636	$0	$0	$0	$0
07540	Roofing & Sheet Metal - M	Metal Roofing 23746	AEPSPAN	$23,746	$0	$0	$23,746	$0	25%	5%	$32,651	$0	$0	$0	$0	$0
07540	Roofing & Sheet Metal - S	Roofing 77460	TRS Metal & Roofing	$77,460	$72,360	$4,400	$700	$0	0%	0%	$0	$0	$0	$0	$0	$0
07540	Roofing & Sheet Metal - M	Metal Roofing 2995	TRS Metal & Roofing	$0	$0	$0	$2,994	$0	25%	5%	$4,117	$0	$0	$0	$0	$0
07540	Roofing & Sheet Metal - M	Steel Aquaduct Gutter	TRS Metal & Roofing	$0	$0	$0	$1,960	$0	23%	7%	$2,597	$0	$0	$0	$0	$0
07900	Caulking - S	Caulking 860	General Caulking	$860	$750	$0	$110	$0	0%	0%	$0	$0	$0	$0	$0	$0
08	**DOORS & WINDOWS**															
08100	H.M. Frames/Doors/Hdwre - L	Shelving Brackets-m	Knape And Vogt	$2,982	$0	$0	$2,982	$0	23%	7%	$3,951	$0	$0	$0	$0	$0
08100	H.M. Frames/Doors/Hdwre - M	H.M. Frames/Doors/Hdwre 29091	Brickson-Shaw	$29,198	$0	$0	$29,198	$0	0%	0%	$0	$0	$0	$0	$0	$0
08210	Wood Doors / Hdwre - S	Custom Pulls 4800	Badger Village Black	$4,800	$0	$0	$4,800	$0	59%	33%	$18,120	$4,800	$0	$0	$0	$0
08210	Skyblend - M	Wood Doors 74045	Wallenfang Custom	$2,811	$0	$0	$2,811	$0	100%	0%	$14,055	$0	$0	$2,811	$0	$0
08210	Custom Wood Cabinets - S	Wood Doors 74045	Wallenfang Custom	$74,045	$70,368	$0	$3,677	$0	0%	0%	$0	$0	$0	$0	$0	$0
08330	Roll-Up Doors - S	Roll-Up Doors 10426	Overhead Door Co of WI	$10,426	$790	$0	$9,636	$0	0%	0%	$0	$0	$0	$0	$0	$0
08810	Glass & Glazing - L	Custom Wood Windowshardware		$159	$159	$0	$0	$0	0%	0%	$0	$0	$0	$0	$0	$0
08810	Glass & Glazing - M	Aluminum Clad Windows 88873.20	Verhalen, Inc.	$88,873	$0	$0	$88,873	$0	0%	20%	$44,437	$88,873	$0	$0	$0	$0
08810	Glass & Glazing - M	Custom Wood Windows 67300	Milwaukee Millwork	$67,330	$0	$0	$67,330	$0	0%	0%	$0	$67,330	$67,330	$0	$0	$0
09	**FINISHES**															
09130	Clay Plaster - S	Plaster 6900	Acorn Enterprises	$6,900	$5,100	$300	$1,500	$0	0%	0%	$0	$0	$0	$0	$0	$0
09300	Tile / Slate Walls - S	Ceramic Tile 5633	Sergenian's Floor	$5,633	$4,107	$0	$1,526	$0	0%	0%	$0	$0	$0	$0	$0	$0
09750	Wood Floor - M	Bona Floor Finish & Sealant		$1,296	$0	$0	$1,296	$0	0%	0%	$0	$0	$0	$0	$0	$0
09750	Wood Floor - S	Wood Flooring 13785	Acorn Enterprises	$13,785	$10,432	$3,103	$250	$0	0%	0%	$0	$0	$0	$0	$0	$0
09900	Painting - S	Painting 26499.99	Skupniewitz Painting	$26,500	$21,152	$0	$5,348	$0	0%	0%	$0	$0	$0	$0	$0	$0
09900	Drywall Tape / Finish - S	Drywall Tape/Finish 4176	Leonard Drywall Inc.	$4,176	$4,176	$0	$0	$0	0%	0%	$0	$0	$0	$0	$0	$0
10	**SPECIALTIES**															
10000	Fire Ext. & Cabinets - M	Fire Ext. - 569	Best Specialties	$569	$0	$0	$569	$0	0%	0%	$0	$0	$0	$0	$0	$0
10000	Toilet Partitions & Accessories - M	Toilet Accessories 3051	Best Specialties	$3,051	$0	$0	$3,051	$0	20%	45%	$6,483	$0	$0	$0	$0	$0
10440	Signs - M			$242	$0	$0	$242	$0	0%	0%	$0	$0	$0	$0	$0	$0
11	**EQUIPMENT**															
11500	Casework - S	Custom Casework 73974	Wallenfang Custom	$73,974	$65,638	$200	$8,136	$0	0%	0%	$0	$0	$0	$0	$0	$0
	TOTAL			**$2,550,591**	**$1,389,447**	**$96,764**	**$1,069,334**	**$14,026**			**$573,469**	**$634,750**	**$392,227**	**$4,987**	**$330,907**	**$258,267**

Table A.1: ALF LEED Calculator
Source: Courtesy of Boldt Construction

LEED® CREDIT INFORMATION

Please complete the following information in all appropriate categories. Write "N/A" if not applicable to the product. Use one documentation sheet for each product or material (i.e. tile and grout each get their own sheet). Attach any other required information to this sheet (i.e. product cut sheet, Material Safety Data Sheet, letters from manufacturers, etc. as indicated in the project LEED Submittal specifications Section 01015 Environmental Goals.

MATERIALS & RESOURCES (MR)

MR C4.1 – Recycled Content: Specify 25%
MR C4.2 – Recycled Content; Specify 50%
Does the product contain post-consumer or post-industrial content? Y N
Percentage of Post-Consumer content: ______97______%
Percentage of Post-Industrial content: ______3_______%

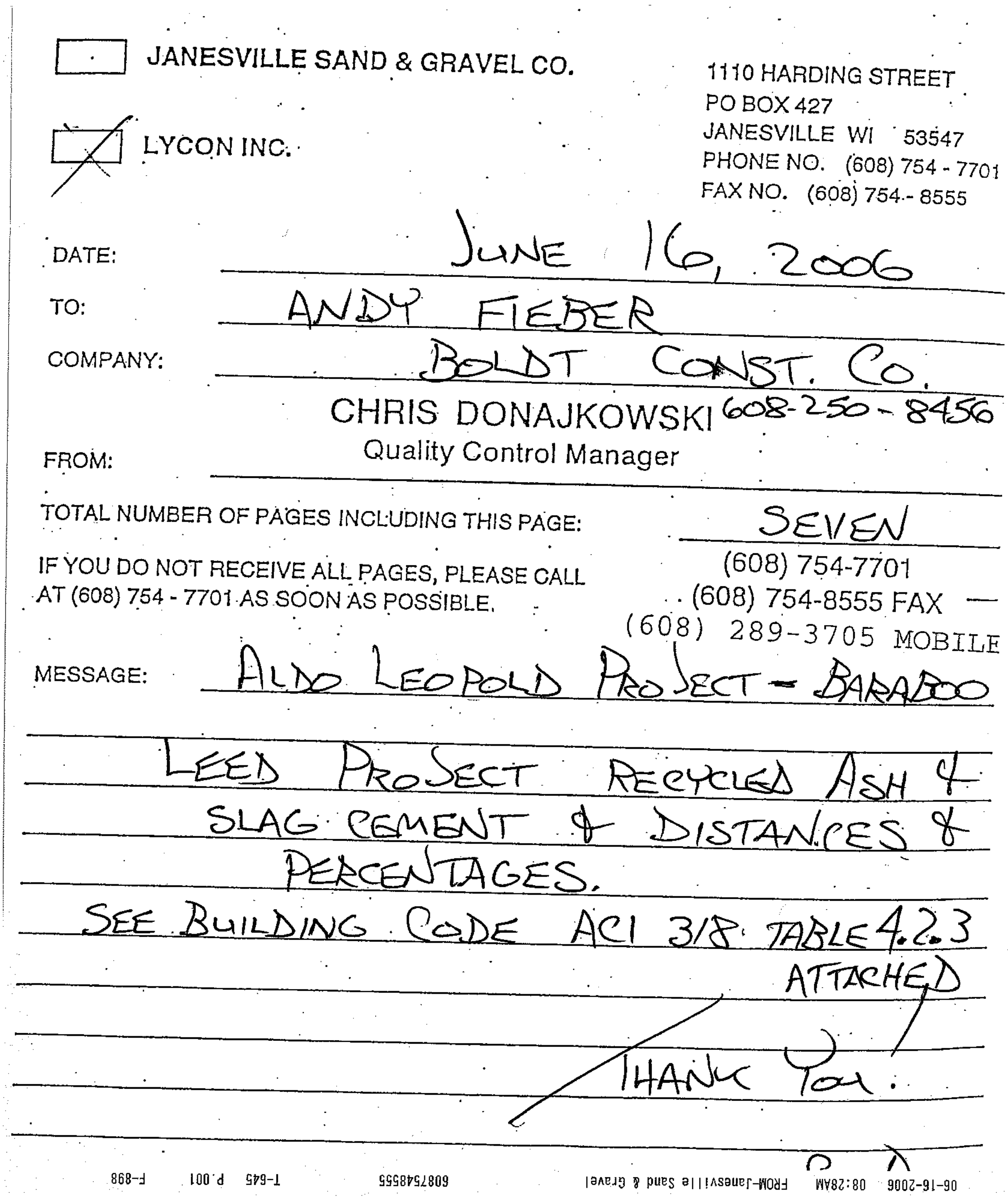
MR C5.1 – Local / Regional Materials; 20% Manufactured Locally
Provide the materials / product manufacturer's final place of assembly / fabrication location.
City, State: __________________________ Distance to the jobsite in miles: _________

MR C5.2 – Local / Regional Materials; of 20% Above, 50% Harvested Locally
Provide the material / product manufacturer's extraction, harvesting or recovering location.
City, State: __________________________ Distance to the jobsite in miles: _________

Product Name	Locally Harvested Material Type	% of Harvested Material (by weight)	Product Cost ($)

Table A.2: Rebar Recycled Content
Source: Courtesy of Boldt Construction

APPENDIX B
CONCRETE & MASONRY



JANESVILLE SAND & GRAVEL CO.

LYCON INC.

1110 HARDING STREET
PO BOX 427
JANESVILLE WI 53547
PHONE NO. (608) 754 - 7701
FAX NO. (608) 754 - 8555

DATE: JUNE 16, 2006

TO: ANDY FIEBER

COMPANY: BOLDT CONST. CO.

FROM: CHRIS DONAJKOWSKI 608-250-8456
Quality Control Manager

TOTAL NUMBER OF PAGES INCLUDING THIS PAGE: SEVEN

IF YOU DO NOT RECEIVE ALL PAGES, PLEASE CALL AT (608) 754 - 7701 AS SOON AS POSSIBLE.

(608) 754-7701
(608) 754-8555 FAX
(608) 289-3705 MOBILE

MESSAGE: ALDO LEOPOLD PROJECT - BARABOO

LEED PROJECT RECYCLED ASH & SLAG CEMENT & DISTANCES & PERCENTAGES.

SEE BUILDING CODE ACI 318 TABLE 4.2.3 ATTACHED

THANK YOU!

06-16-2006 08:28AM FROM-Janesville Sand & Gravel 6087548555 T-645 P.001 F-898

Figure B.1: Middleton Construction Concrete Data
Source: Courtesy of the Boldt Construction Company

06/09/2006 13:00 FAX 6086358838 MIDDLETON CONSTRUCTION 002

☐ JANESVILLE SAND & GRAVEL CO.

☒ LYCON INC.

1110 HARDING STREET
PO BOX 427
JANESVILLE WI 53547
PHONE NO. (608) 754 - 7701
FAX NO. (608) 754 - 8555

DATE: MAY 23, 2006

TO: MR. BILL KELLOGG

COMPANY: MCI

FROM: CHRIS DONAJKOWSKI
Quality Control Manager

TOTAL NUMBER OF PAGES INCLUDING THIS PAGE: SEVEN

IF YOU DO NOT RECEIVE ALL PAGES, PLEASE CALL AT (608) 754 - 7701 AS SOON AS POSSIBLE.

(608) 754-7701
(608) 754-8555 FAX
(608) 289-3705 MOBILE

MESSAGE: ALDO LEOPOLD CENTER

CONCRETE DATA & CERTS.

THANK YOU!

05-23-2006 08:36AM FROM-Janesville Sand & Gravel 6087548555 T-133 P.001 F-999

Figure B.2: Middleton Construction Concrete Data
Source: Courtesy of the Boldt Construction Company

06/09/2006 13:01 FAX 6086358838 MIDDLETON CONSTRUCTION 003

LYCON INC

GENERAL OFFICES
1110 Harding Street P.O. Box 427
Janesville, Wisconsin 53547-0427

(608) 754-7701
(800) 262-8604
(608) 754-8555 FAX

SERVING THE FOLLOWING AREAS

ADAMS COUNTY	IOWA COUNTY
COLUMBIA COUNTY	JEFFERSON COUNTY
DANE COUNTY	RICHLAND COUNTY
DODGE COUNTY	ROCK COUNTY
FOND DU LAC COUNTY	SAUK COUNTY
GREEN COUNTY	SHEBOYGAN COUNTY
GREEN LAKE COUNTY	WALWORTH COUNTY

MAY 23, 2006

PROJECT: ALDO LEOPOLD FOUNDATION LEGACY CENETER
MADISON, WISCONSIN

CONTRACTOR: MIDDLETON CONSTRUCTION INC.
ARLINGTON, WISCONSIN

FOOTINGS	3000 PSI	4″ SLUMP	NO AIR
EXTERIOR	4000 PSI	4″ SLUMP	AIR ENTRAINED
INTERIOR	4000 PSI	4″ SLUMP	NO AIR
MASONRY GROUT	3000 PSI	8″ SLUMP	NO AIR

MIXES PER ACI 318 BUILDING CODE FIELD EXPERIENCE METHOD DATA ATTACHED.
ASTM C-494 CONCRETE ADMIXTURES ADDED AT CONTRACTOR'S OPTION.
ENTRAINED AIR TOLERANCE OF +/- 1.5% AS PER ACI 318-05 SEC. 4.2.1
ACI 301-99 TABLE 3.4.1 AND ASTM C94-00 SECTION 7.2.
INTERIOR FLOOR MIX AS PER WISCONSIN BUILDING CODE AMERICAN CONCRETE INSTITUTE 302 FLOORS SECTION 6.2.4 WATER/CEMENT RATIO 0.47 TO 0.53.
ALL AGGREGATE WEIGHTS ARE SATURATED SURFACE DRY CONDITION.
ALL FREE MOISTURE MUST BE COMPENSATED AT TIME OF MIXING.
MATERIALS OF SIMILAR QUALITY MAY BE UTILIZED DUE TO AVAILABILITY.
THIS SUBMITTAL IS PROPRIETARY INFORMATION OF LYCON, INC. AND MAY NOT BE REPRODUCED WITHOUT EXPRESS PERMISSION OF THIS OFFICE.
INSTALLATION OF CONCRETE CONVEYS APPROVAL OF THIS SUBMITTAL.
ANY ALTERATIONS TO THESE MIXES MUST BE SUBMITTED TO THIS OFFICE.
PLEASE CALL WITH ANY QUESTIONS REGUARDING THIS SUBMITTAL.

LYCON INC.

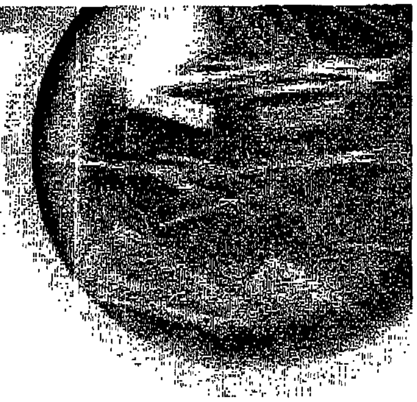
CHRIS DONAJKOWSKI
QUALITY CONTROL MANAGER

05-23-2006 08:36AM FROM-Janesville Sand & Gravel 6087548555 T-133 P.002 F-999

Figure B.3: Concrete Data - Middleton Construction
Source: Courtesy of the Boldt Construction Company

FIBERMESH® 300

PRODUCT DATA SHEET



FIBERMESH® 300 SYNTHETIC FIBER

Fibermesh 300, formerly InForce™ e3,® micro-reinforcement system for concrete—100 percent virgin homopolymer polypropylene fibrillated fibers with e3® patented technology containing no reprocessed olefin materials. Specifically engineered and manufactured in an ISO 9001-2000 certified facility to an optimum gradation for use as concrete secondary reinforcement at a minimum of 0.1% by volume (1.5 pounds per cubic yard, 0.9 kg per cubic meter). UL Classified. Complies with National Building Codes and ASTM C 1116 Type III 4.1.3., ASTM C 1116 Performance Level I and Residual Strength.

ADVANTAGES

Accepted by National Codes as an alternate method of secondary reinforcing to traditional systems • Non-magnetic • Rustproof • Alkali proof • Requires no minimum amount of concrete cover • Is always positioned in compliance with codes • Safe and easy to use • Save time and hassle

FEATURES & BENEFITS

- Alternate construction system to traditional secondary reinforcing in concrete
- Inhibits and controls the formation of intrinsic cracking in concrete
- Reinforces against impact forces
- Reinforces against the effect of shattering forces
- Reinforces against material loss from abrading forces
- Reinforces against water migration
- Provides improved durability
- Imparts toughness to hardened concrete
- Reduces plastic shrinkage and settlement cracking
- Provides residual strength

PRIMARY APPLICATIONS

Applicable to all types of concrete which demonstrate a need for toughness, resistance to intrinsic cracking and improved water tightness.

- Slab-on-grade
- Sidewalks
- Driveways
- Stucco
- Curbs
- Shotcrete
- Composite metal decks
- Slope paving
- Overlays & toppings

DO SPECIFY FIBERMESH 300 FIBERS

- Reduced plastic shrinkage cracking
- Alternative to traditional reinforcement
- Improved impact, shatter and abrasion resistance
- Improved residual strength
- Reduced water migration and damage from freeze/thaw
- Improved durability
- Areas requiring non-metallic materials

DO NOT SPECIFY FIBERMESH 300 FIBERS

- Crack control from external stresses
- Increasing joint spacing beyond ACI and PCA guidelines
- Decreasing thickness of slabs
- Replacing any moment or structural steel

CHEMICAL AND PHYSICAL PROPERTIES:

Absorption	Nil	Melt Point	324°F (162°C)
Specific Gravity	0.91	Ignition Point	1100°F (593°C)
Fiber Length*	Graded	Thermal Conductivity	Low
Electrical Conductivity	Low	Alkali Resistance	Alkali Proof
Acid & Salt Resistance	High		

*Also available in single cut lengths

SI® Concrete Systems

For those who prefer performance to tradition.

05-23-2006 08:36AM FROM-Janesville Sand & Gravel 6087548555 T-133 P.003/007 F-999

Figure B.4: Concrete Data - Middleton Construction
Source: Courtesy of the Boldt Construction Company

```
ac.                                3000   PSI   FOOTINGS                         5/23/2006    Page: 1
ct Code Statistics
days)7        28
specs:27      57
.Str :3900    5860
n.Str :2200   4228
vg.Str :2921  5007
SD  Str :405  414
Density :0.0  0.0

  Last 9999 records,
```

5007 PSI AVE.

Date	Individual Samples Ticket		Sample	Plant	Ages, Strengths, Densities			
31Jan06	3000	360307	1	10	7 3130	, 28 5650	, 28 5810	,
31Jan06	3000	360337	1	10	7 2730	, 28 5030	, 28 5090	,
1Feb06	3000	360721	1	10	7 2200	, 28 4670	, 28 4810	,
2Feb06	3000	360915	1	10	7 2380	, 28 4990	, 28 4620	,
3Feb06	3000	361230	1	10	7 3010	, 28 5610	, 28 5390	,
9Feb06	3000	362194	1	10	7 2740	, 28 5060	, 28 5560	,
15Feb06	3000	363245	1	3	7 2800	, 28 5070	, 28 5080	,
1Mar06	3000	364831	1	10	7 3180	, 28 5540	, 28 5370	,
2Mar06	3000	365064	1	10	7 2920	, 28 5090	, 28 5260	,
3Mar06	3000	365292	1	3	7 2750	, 28 4650	, 28 4850	,
8Mar06	3000	366226	1	3	7 3020	, 28 4680	, 28 5080	,
14Mar06	3000	367305	1	3	7 3750	, 28 5860	, 28 5660	,
15Mar06	3000	367670	1	3	7 3380	, 28 4990	, 28 5270	,
15Mar06	3000	367711	1	3	7 2630	, 28 4460	, 28 4540	,
22Mar06	3000	368878	1	3	7 3140	, 28 4910	, 28 4680	,
23Mar06	3000	369131	1	2	7 3090	, 28 4990	, 28 5300	,
24Mar06	3000	369457	1	2	7 2570	, 28 5220	, 28 5260	,
4Apr06	3000	371959	1	2	7 2740	, 28 5120	, 28 4950	,
5Apr06	3000	372562	1	3	7 2470	, 28 4300	, 28 4660	,
11Apr06	3000	374168	1	3	7 2950	, 28 4690	, 28 4990	,
12Apr06	3000	374524	1	2	7 3100	, 28 4630	, 28 4690	,
12Apr06	3000	374588	1	3	7 3590	, 28 5140	, 28 5270	,
13Apr06	3000	375000	1	3	7 3900	, 28 5080	, 28 5580	,
13Apr06	3000	375051	A	5	28 5534	, 28 5506	, 28 4822	,
14Apr06	3000	375567	A	5	7 2644	, 28 5073	, 28 5130	,
17Apr06	3000	376130	A	5	7 2571	, 28 4589	, 28 4436	,
20Apr06	3000	377914	A	4	7 2947	, 28 4307	, 28 4345	,
20Apr06	3000	378000	A	5	7 2535	, 28 4228	, 28 4252	,

END OF REPORT

Date 23-May-2006 LYCON INC.
Time 08:07 Item Listing

Item Code	Description	Short Descr	Item Category	Inventory Item Code	Keep in Inventory	Resale Item
63804861	3000 PSI 6-2 CONCRETE NA	3000 PSI 6-2 NA	03376 4 B		[ ]	[X]

Constituents	Item Code	Short Descr	Quantity	
3 MIDDLETON PLANT	12210000	FINE AGG/CONCRET	1509.00	lb
	18210000	COARSE AGG/ 1 1/	778.00	lb
	23001000	WATER	30.00	ga
	16210000	COARSE AGG/ 3/4"	1166.00	lb
	21005000	LAFARGE - CEMENT	230.00	lb
	21014000	NEW/CEM 120	100.00	lb -26%
	21009000	FLY ASH - BULK	50.00	lb - 13%

06-16-2006 08:29AM FROM-Janesville Sand & Gravel 6087548555 T-645 P.005/008 F-898

Figure B.5: Footings Concrete Mix Data
Source: Courtesy of the Boldt Construction Company

Inc. 4000 PSI INTERIOR 5/23/2006 Page: 1

ct Code Statistics

(days)	7	28
Specs	:23	57
x.Str	:6480	7770
in.Str	:3230	4230
Avg.Str	:4212	6208
SD Str	:687	782
Density	:0.0	0.0

Last 9999 records,

6208 PSI AVE.

Individual Samples

Date	P/Code	f'c	Ticket	Sample	Plant	Ages, Strengths, Densities		
14Jul05	65206896	4000	990482	M-10-144	10	28 4700 ,	28 4810 ,	
14Jul05	65206896	4000	990565	1	10	7 4180 ,	28 6060 ,	28 6110 ,
14Jul05	65206896	4000	990631	1	10	7 3840 ,	28 5860 ,	28 5880 ,
14Jul05	65206896	4000	990960	1	3	7 4480 ,	28 6670 ,	28 6770 ,
15Jul05	65206896	4000	991224	1	2	7 3960 ,	28 5430 ,	28 5720 ,
19Jul05	65206896	4000	993004	1	3	7 3690 ,	28 6350 ,	28 6370 ,
20Jul05	65206896	4000	993089	1	2	7 4190 ,	28 6640 ,	28 6330 ,
26Jul05	65206896	4000	995157	1	3	7 4070 ,	28 6580 ,	28 6510 ,
27Jul05	65206896	4000	995629	1	3	7 3390 ,	28 6450 ,	28 6390 ,
27Jul05	65206896	4000	995937	1	3	7 3810 ,	28 6740 ,	28 6800 ,
28Jul05	65206896	4000	996334	1	3	7 4160 ,	28 6270 ,	28 6230 ,
29Jul05	65206896	4000	997031	1	3	7 4460 ,	28 5970 ,	28 6400 ,
29Jul05	65206896	4000	997057	R-19-34	2	28 4230 ,	28 4390 ,	
30Jul05	65206896	4000	997528	1	2	7 4100 ,	28 4940 ,	28 4840 ,
1Aug05	65206896	4000	997812	S-2-206	2	28 4990 ,	28 5110 ,	
1Aug05	65206896	4000	998139	1	3	7 4200 ,	28 6670 ,	28 6570 ,
2Aug05	65206896	4000	998359	1	3	7 3940 ,	28 6150 ,	28 5820 ,
4Aug05	65206896	4000	999750	1	3	7 3580 ,	28 6070 ,	28 5980 ,
9Aug05	65206896	4000	301236	1	3	7 3820 ,	28 6610 ,	28 6640 ,
11Aug05	65206896	4000	302710	1	3	7 4500 ,	28 6720 ,	28 7560 ,
16Aug05	65206896	4000	304091	S-3-217	3	28 6150 ,	28 6470 ,	
28Oct05	65206896	4000	337174	1	3	7 3820 ,	28 6920 ,	28 6670 ,
8Nov05	65206896	4000	341629	1213A	9	7 3230 ,	28 5500 ,	
17Nov05	65206896	4000	345982	1	3	7 5150 ,	28 7770 ,	28 7670 ,
30Nov05	65206896	4000	348988	M-3-315	3	28 5800 ,	28 5840 ,	
8Dec05	65206896	4000	350473	1	3	7 4740 ,	28 6900 ,	28 6790 ,
21Dec05	65206896	4000	352885	1	3	7 6480 ,	28 6970 ,	28 6850 ,
9Jan06	65206896	4000	355803	M-3-7	3	28 5820 ,	28 5870 ,	
19Jan06	65206896	4000	358158	1	3	7 5090 ,	28 7580 ,	28 6940 ,

END OF REPORT

Date 23-May-2006
Time 08:13

LYCON INC.
Item Listing

Item Code	Description	Short Descr	Item Category	Inventory Item Code	Keep in Inventory	Resale Item
65426897	4000 PSI #67 NA	4000 PSI #67 NA	03541 5.75 B		[ ]	[X]

Constituents

	Item Code	Short.Descr	Quantity	
3 MIDDLETON PLANT	12210000	FINE AGG/CONCRET	1549.00	lb
	16210000	COARSE AGG/ 3/4"	878.00	lb
	13060000	3/4" LIMESTONE/C	878.00	lb
	21005000	LAFARGE - CEMENT	350.00	lb
	21009000	FLY ASH - BULK	95.00	lb – 18%
	21014000	NEW/CEM 120	95.00	lb – 18%
	23001000	WATER	31.00	ga

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Figure B.6: Interior Floor Concrete Mix Data
Source: Courtesy of the Boldt Construction Company

Inc.

4000 PSI EXTERIOR & WALLS

5/23/2006 Page: 1

Product Code Statistics

Age(days)	7	28
No. specs	:27	58
Max.Str	:5020	6820
Min.Str	:3070	4920
Avg.Str	:4017	5894
SD Str	:571	457
Density	:0.0	0.0

Last 9999 records,

5894 PSI AVE.

Individual Samples

Date	P/Code	f'c	Ticket	Sample	Plant	Ages, Strengths, Densities		
2Mar06	65706827	4000	364915	1227A	9	7 4380 ,	28 6190 ,	28 6030 ,
2Mar06	65706827	4000	364918	G-9-34	9	28 5640 ,	28 5640 ,	
2Mar06	65706827	4000	364922	12280A	9	7 4080 ,	28 5680 ,	28 5740 ,
2Mar06	65706827	4000	364938	G-9-35	9	28 5730 ,	28 5680 ,	
2Mar06	65706827	4000	364946	12281A	9	7 4450 ,	28 5770 ,	28 5730 ,
2Mar06	65706827	4000	364951	12283A	9	7 4370 ,	28 6010 ,	28 6140 ,
2Mar06	65706827	4000	364963	12282A	9	7 4100 ,	28 5340 ,	28 5630 ,
7Mar06	65706827	4000	365762	12284A	9	7 4040 ,	28 5190 ,	28 5070 ,
9Mar06	65706827	4000	366505	12286A	9	7 3220 ,	28 5990 ,	28 6000 ,
13Mar06	65706827	4000	367014	12287A	9	7 4320 ,	28 6690 ,	28 6570 ,
14Mar06	65706827	4000	367233	12288A	9	7 3860 ,	28 5560 ,	28 5580 ,
15Mar06	65706827	4000	367706	12291	9	7 3610 ,	28 6020 ,	28 5930 ,
15Mar06	65706827	4000	367745	12292A	9	7 3120 ,	28 5540 ,	28 5080 ,
15Mar06	65706827	4000	367788	12293A	9	7 3310 ,	28 5550 ,	28 5620 ,
20Mar06	65706827	4000	368381	12294A	9	7 3690 ,	28 6060 ,	28 5820 ,
21Mar06	65706827	4000	368691	12295A	9	7 4700 ,	28 5870 ,	28 5990 ,
22Mar06	65706827	4000	368949	12296A	9	7 3850 ,	28 5970 ,	28 5990 ,
3Apr06	65706827	4000	371511	12300A	9	7 4020 ,	28 6010 ,	28 6190 ,
5Apr06	65706827	4000	372374	12301A	9	7 3840 ,	28 6130 ,	28 6010 ,
5Apr06	65706827	4000	372415	1	3	7 4620 ,	28 6470 ,	28 6510 ,
6Apr06	65706827	4000	372791	1	3	7 4780 ,	28 5510 ,	28 5490 ,
10Apr06	65706827	4000	373375	12302A	9	7 4210 ,	28 6290 ,	28 6340 ,
10Apr06	65706827	4000	373474	12303A	9	7 4200 ,	28 6820 ,	28 6820 ,
10Apr06	65706827	4000	373509	1	2	7 5020 ,	28 6630 ,	28 6280 ,
11Apr06	65706827	4000	374125	1	2	7 4560 ,	28 6310 ,	28 5770 ,
13Apr06	65706827	4000	374903	1	3	7 4710 ,	28 6770 ,	28 6450 ,
17Apr06	65706827	4000	375798	12309A	9	7 3070 ,	28 4920 ,	28 5040 ,
17Apr06	65706827	4000	375875	12310A	9	7 3220 ,	28 5580 ,	28 5490 ,
17Apr06	65706827	4000	375943	12311A	9	7 3110 ,	28 5450 ,	28 5510 ,

END OF REPORT

Date 23-May-2006
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LYCON INC.
Item Listing

Item Code	Description	Short Descr	Item Category	Inventory Item Code	Keep in Inventory	Resale Item
65706827	4000 PSI #67 AE	4000 PSI #67 AE	03564 6 B		[ ]	[X]

Constituents

	Item Code	Short Descr	Quantity	
3 MIDDLETON PLANT	12210000	FINE AGG/CONCRET	1364.00	lb
	21005000	LAFARGE - CEMENT	370.00	lb
	21014000	NEW/CEM 120	100.00	lb — 17.5%
	21009000	FLY ASH - BULK	100.00	lb — 17.5%
	20997000	AIR ENTRAINING-F	5.00	oz
	16210000	COARSE AGG/ 3/4"	878.00	lb
	13060000	3/4" LIMESTONE/C	878.00	lb
	23001000	WATER	28.70	ga

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Figure B.7: Foundation Wall Concrete Mix Data
Source: Courtesy of the Boldt Construction Company

Inc. — 3000 PSI CMU BLOCK FILL GROUT — 5/23/2006 Page: 1

Product Code Statistics

Age(days)	7	28
No.Specs	:1	26
Max.Str	:4900	6850
Min.Str	:4900	5100
Avg.Str	:4900	6052
SD Str	:0	488
Density	:0.0	0.0

Last 9999 records,

6052 PSI

Individual Samples

Date	P/Code	f'c	Ticket	Sample	Plant	Ages, Strengths, Densities
25Apr03	36588658	0	710473	R-14-26	14	28 5940 , 28 6250 ,
8May03	36588658	0	715158	R-14-34	14	28 5610 , 28 5400 ,
29May03	36588658	0	723526	R-14-50	14	28 6440 , 28 6220 ,
6Jun03	36588658	0	727563	S-2-175	2	28 6200 , 28 6300 ,
11Aug03	36588658	0	755384	R-14-102	14	28 5730 , 28 5800 ,
30Sep03	36588658	0	776919	R-14-140	14	28 6800 , 28 6650 ,
31Oct03	36588370	4000	790732	1	4	7 4900 , 28 5790 , 28 5920 ,
22Jan04	36588658	0	809511	R-14-03	14	28 6610 , 28 6540 ,
1Oct04	36588658	0	899602	R-14-75	14	28 5910 , 28 5480 ,
7Dec04	36588658	0	925540	R-14-91	14	28 6690 , 28 6850 ,
20Apr05	36588658	0	953131	R-14-10	14	28 5770 , 28 5660 ,
22Jun05	36588658	0	981050	R-14-26	14	28 5220 , 28 5100 ,
4Aug05	36588658	0	999497	R-14-40	14	28 6330 , 28 6130 ,

END OF REPORT

Date 23-May-2006
Time 08:09

LYCON INC.
Item Listing

Item Code	Description	Short Descr	Item Category	Inventory Item Code	Keep in Inventory	Resale Item
66008883	CMU GROUT C-476	CMU GROUT C-476	03611 6.5 B		[ ]	[X]

Constituents

	Item Code	Short Descr	Quantity	
3 MIDDLETON PLANT	12210000	FINE AGG/CONCRET	1741.00	lb
	14210000	COARSE AGG/ 3/8"	1100.00	lb
	21005000	LAFARGE - CEMENT	300.00	lb
	21009000	FLY ASH - BULK	150.00	lb - 25%
	21014000	NEW/CEM 120	150.00	lb - 25%
	23001000	WATER	45.00	ga

*** 1 record(s) listed ***

06-16-2006 08:31AM FROM-Janesville Sand & Gravel 6087548555 T-645 P.008/008 F-898

Figure B.8: CMU Block Fill Grout Mix Data
Source: Courtesy of the Boldt Construction Company

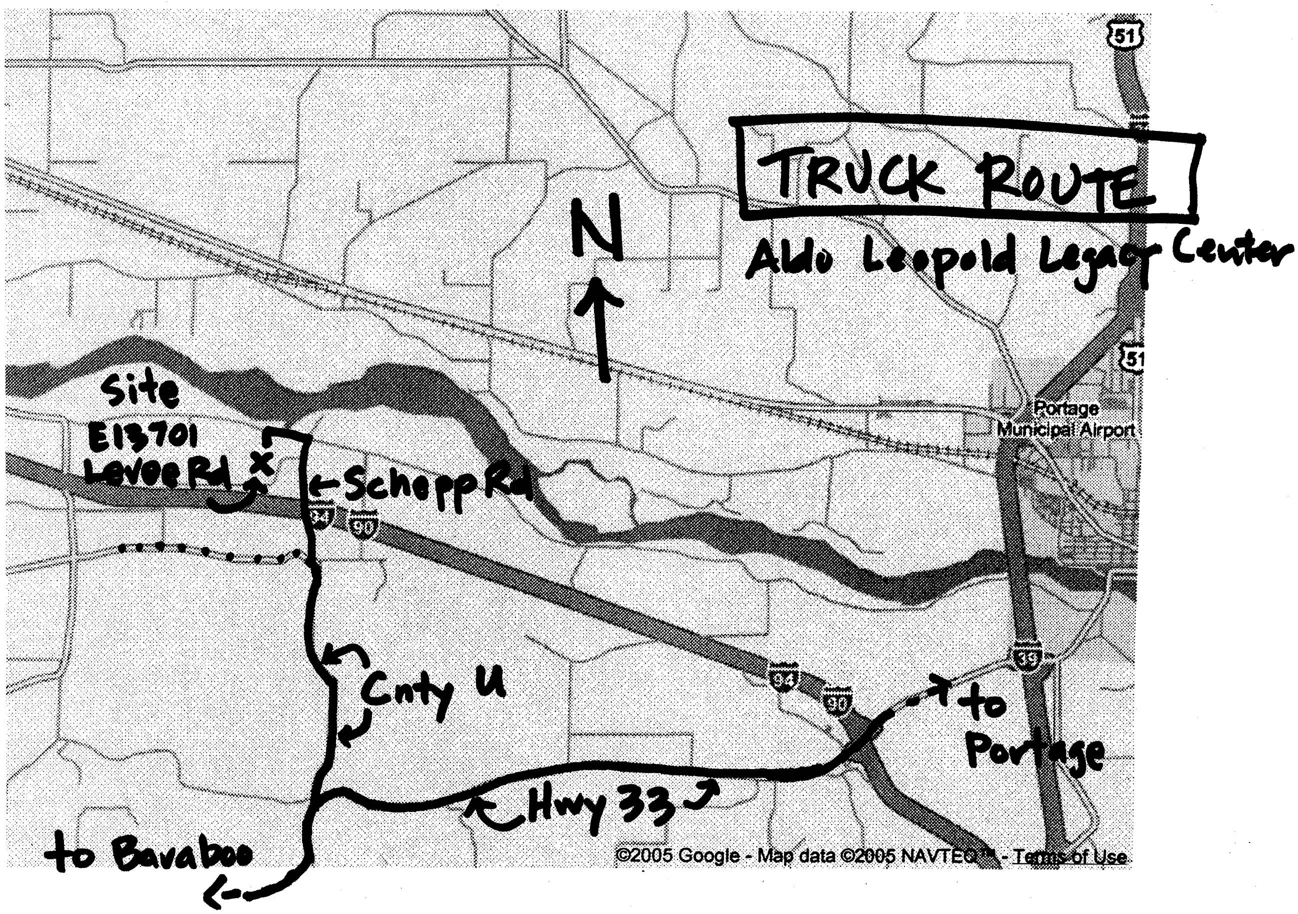
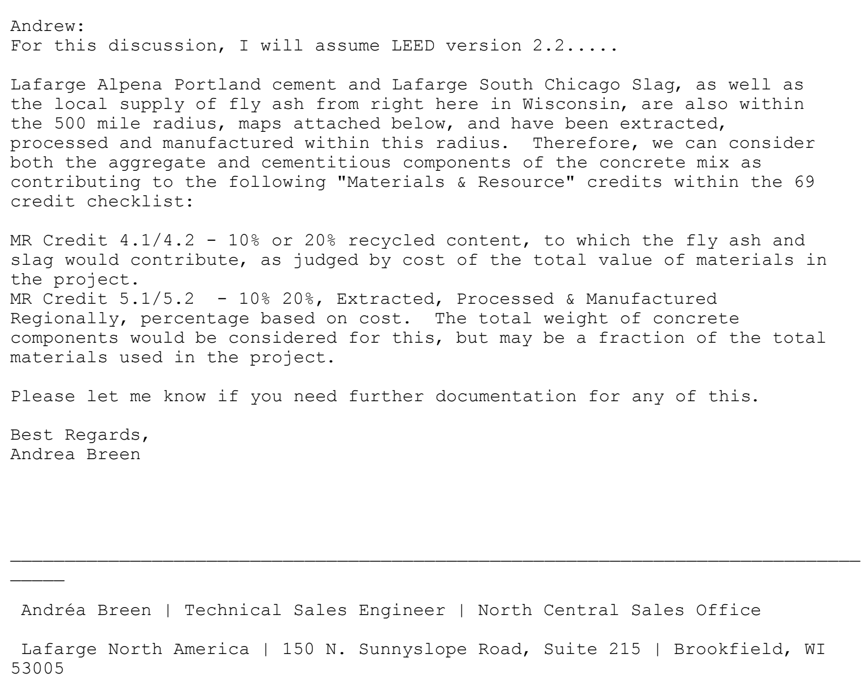


Figure B.9: ALF Truck Route
Source: Courtesy of the Boldt Construction Company



Andrew:
For this discussion, I will assume LEED version 2.2.....

Lafarge Alpena Portland cement and Lafarge South Chicago Slag, as well as the local supply of fly ash from right here in Wisconsin, are also within the 500 mile radius, maps attached below, and have been extracted, processed and manufactured within this radius. Therefore, we can consider both the aggregate and cementitious components of the concrete mix as contributing to the following "Materials & Resource" credits within the 69 credit checklist:

MR Credit 4.1/4.2 - 10% or 20% recycled content, to which the fly ash and slag would contribute, as judged by cost of the total value of materials in the project.
MR Credit 5.1/5.2 - 10% 20%, Extracted, Processed & Manufactured Regionally, percentage based on cost. The total weight of concrete components would be considered for this, but may be a fraction of the total materials used in the project.

Please let me know if you need further documentation for any of this.

Best Regards,
Andrea Breen

Andréa Breen | Technical Sales Engineer | North Central Sales Office

Lafarge North America | 150 N. Sunnyslope Road, Suite 215 | Brookfield, WI 53005

Figure B.10: ALF - Lafarge
Source: Courtesy of the Boldt Construction Company

Appendix C
Leopold Timber Harvest

Figure C.1: Wood Harvest
Source: Courtesy of the Aldo Leopold Foundation

Figure C.2: Wood Harvest
Source: Courtesy of the Aldo Leopold Foundation

Figure C.3: Wood Harvest
Source: Courtesy of the Aldo Leopold Foundation

Figure C.4: Wood Harvest
Source: Courtesy of the Aldo Leopold Foundation

Building	hidden	Interior/Exterior	wood species	Party Resp.	Usage	Location on plan	size	quantity	Thickness	Width	Length (feet)	Length (in.)	board feet	Thickness Finished	Width Finished	Board Feet Finished
EQUATION TEST								1	1	12	1.00	12	1	1	12	1
Exhibit Hall		int	pine	ALF	Low Beams	A.7 22-26	**8x8x12'-0"**	**4**	**8**	**8**	**12.00**	144	256	7.5	7.5	225
Exhibit Hall		int	pine	ALF	Columns	A.7 22-26	**8x10x16'4**	**5**	**8**	**10**	**16.30**	196	543	7.5	9.5	484
Exhibit Hall		int	pine	ALF	Columns	C23-26	**8x10x12'3**	**4**	**8**	**10**	**12.25**	147	327	7.5	9.5	291
Exhibit Hall		int	pine	ALF	beams	C23-26	**8x10x12'-0"**	**3**	**8**	**10**	**12.00**	144	240	7.5	9.5	214
Exhibit Hall		int	pine	ALF	beams	C22-23	**8x10x10'-8"**	**1**	**8**	**10**	**10.67**	128	71	7.5	9.5	63
Exhibit Hall	hidden	int	pine	ALF	High Beams	A.7 22-26	**8x12x12'-9"**	**2**	**8**	**12**	**12.75**	153	204	7.5	11.5	183
Exhibit Hall	hidden	int	pine	ALF	High Beams	A.7 22-26	**8x12x12'-0"**	**2**	**8**	**12**	**12.00**	144	192	7.5	11.5	173
Mud Room		int	pine	ALF	Beams	G21-22	**8x14x12'4"**	**1**	**8**	**14**	**17.00**	204	159	7.5	13.5	143
Mud Room		int	pine	ALF	Beams	G21-22	**8x14x9'**	**1**	**10**	**14**	**8.25**	99	96	9.5	13.5	88
Mud Room		int	pine	ALF	Columns	G21.5	**8x8x11'**	**1**	**8**	**8**	**11.00**	132	59	7.5	7.5	52
Mud Room		int	pine	ALF	Columns	A.7 21.5	**8x8x9'-8"**	**1**	**8**	**8**	**9.67**	116	52	7.5	7.5	45
Mud Room		int	oak	ALF -	Beams	D 21-22	**8x14x22'6"**	**2**	**8**	**14**	**22.50**	270	420	7.5	13.5	380
Mud Room		int	oak	ALF -	Beams	D 21-22	**8x8x4**	**4**	**8**	**8**	**4.00**	48	85	7.5	7.5	75
Mud Room		int	oak	ALF -	Beams	D 21-22	**2x8xvarious**	**4**	**2**	**8**	**5.00**	60	27	2	7.5	25
Mud Room		int	pine	ALF	Beams	C 21-22	**8x14x15'4"**	**1**	**8**	**14**	**17.00**	204	159	7.5	13.5	143
Mud Room		int	pine	ALF	Beams	C 21-22	**8x14x7'6"**	**1**	**8**	**14**	**7.50**	90	70	7.5	13.5	63
Mud Room		int	pine	ALF	Columns	C 21.5	**8x8x11'-6"**	**1**	**8**	**8**	**11.50**	138	61	7.5	7.5	54
Mud Room		int	pine	ALF	Beams	A.7 21-22	**8x14x9'6""**	**1**	**8**	**14**	**5.00**	60	47	7.5	13.5	42
Mud Room		int	pine	ALF	Beams	A.7 21-22	**8x14x15'6"**	**1**	**8**	**14**	**17.00**	204	159	7.5	13.5	143
Mud Room		int	pine	ALF	Beams	A.7 -C 22	**10x14x10"**	**1**	**10**	**14**	**10.00**	120	117	9.5	13.5	107
Mud Room		int	pine	ALF	Beams	A.7 21-22	**8x8x6'**	**2**	**8**	**8**	**6.00**	72	64	7.5	7.5	56
Mud Room		int	pine	ALF	Columns	C 21	**6x8x13'**	**1**	**6**	**8**	**13.00**	156	52	5.5	7.5	45
Staff Building		int	pine	ALF	low Beams	D&G 10-13, 16-20	**8x8x9'**	**14**	**8**	**8**	**9.00**	108	672	7.5	7.5	591
Staff Building		int	pine	ALF	Beams	D &G 13-16	**8x8x6'**	**9**	**8**	**8**	**5.00**	60	240	7.5	7.5	211
Staff Building		int	pine	ALF	Posts	D 8-20	**8x8x16'4"**	**13**	**8**	**8**	**16.30**	196	1130	7.5	7.5	993
Staff Building		int	pine	ALF	Beams	G 8.5-10	**8x8x12'6"**	**4**	**8**	**8**	**12.50**	150	267	7.5	7.5	234
Staff Building		int	pine	ALF	Posts	G 8-20	**8x8x11'3/4"**	**13**	**8**	**8**	**12.00**	144	832	7.5	7.5	731
Staff Building		int	pine	ALF	post	G 21	**8x8x11'3/4"**	**1**	**8**	**8**	**12.00**	144	64	7.5	7.5	56
Staff Building		int	pine	ALF	Beams	D&G 20-21	**8x8x10'6"'**	**2**	**8**	**8**	**10.50**	126	112	7.5	7.5	98
Staff Building		int	pine	ALF	Posts	H 8	**8x8x10'**	**1**	**8**	**8**	**10.00**	120	53	7.5	7.5	47
Staff Building		int	pine	ALF	Posts D21	D 21	**8x10x16'4**	**1**	**8**	**10**	**16.50**	198	110	7.5	9.5	98
Staff Building		int	pine	ALF	high beam d 8-10	D 8-10	**8x12x12**	**1**	**8**	**12**	**12.00**	144	96	7.5	11.5	86
Staff Building		ext	pine	ALF	low Beams	G 8	**8x8x4**	**1**	**8**	**8**	**4.00**	48	21	7.5	7.5	19
Staff Building		ext	pine	ALF	low Beams	H 8-10	**8x10x12**	**1**	**8**	**10**	**12.00**	144	80	7.5	9.5	71
Staff Building		ext	pine	ALF	low Beams	B 8-10	**8x10x12**	**1**	**8**	**10**	**12.00**	144	80	7.5	9.5	71
Staff Building		int	pine	ALF	post	B 8	**8x8x8**	**1**	**8**	**8**	**8.00**	96	43	7.5	7.5	38
Staff Building		int	pine	ALF	low Beams	D 8-9	**8x8x8**	**1**	**8**	**8**	**8.00**	96	43	7.5	7.5	38
Staff Building		int	pine	ALF	post	D 9	**6x8x16**	**1**	**6**	**8**	**16.00**	192	64	5.5	7.5	55
Staff Building		int	pine	ALF	post	G 8.5	**6x8x12**	**1**	**6**	**8**	**12.00**	144	48	5.5	7.5	41
Staff Building		int	pine	ALF	Beams	D 9-10	**8x8x4**	**1**	**8**	**8**	**4.00**	48	21	7.5	7.5	19
Meeting Hall		int	pine	ALF	Truss Parts	R, Q, P, N 1-6	**6x12x18'**	**8**	**6**	**12**	**18.00**	216	864	5.5	11.5	759
Meeting Hall		int	pine	ALF	Truss Parts	R, Q, P, N 1-6	**2x8x16'**	**16**	**2**	**8**	**16.00**	192	341	2	8	341
Meeting Hall		int	pine	ALF	Truss Parts	R, Q, P, N 1-6	**2x8x12'**	**16**	**2**	**8**	**12.00**	144	256	2	8	256
Meeting Hall		int	pine	ALF	Truss Parts	R, Q, P, N 1-6	**2x8x8'**	**16**	**2**	**8**	**8.00**	96	171	2	8	171
Meeting Hall		int	pine	ALF	Truss Parts	R, Q, P, N 1-6	**3x6x various**	**16**	**3**	**6**	**4.00**	48	96	3	6	96
Seed Hall (round log)		int	pine	ALF	truss parts upper cord		**7x7x35**	**6**	**7**	**7**	**35.00**	420	858	7	7	858
Seed Hall (round log)		int	pine	ALF	truss parts lower cord		**7x7x28**	**6**	**7**	**7**	**28.00**	336	686	7	7	686
Seed Hall (round log)		int	pine	ALF	truss vertical		**6x6x1**	**6**	**6**	**6**	**1.00**	12	18	6	6	18
Seed Hall (round log)		int	pine	ALF	truss vertical		**6x6x2**	**6**	**6**	**6**	**2.00**	24	36	6	6	36
Seed Hall (round log)		int	pine	ALF	truss vertical		**6x6x4**	**6**	**6**	**6**	**4.00**	48	72	6	6	72
Seed Hall (round log)		int	pine	ALF	roof purlin		**6x6x9.33**	**40**	**6**	**6**	**9.33**	112	1120	6	6	1120
Seed Hall (round log)		int	pine	ALF	roof purlin		**6x6x12**	**26**	**6**	**6**	**12.00**	144	936	6	6	936
Seed Hall (round log)		int	pine	ALF	Columns		**7x7x11**	**6**	**7**	**7**	**11.00**	132	270	7	7	270
Seed Hall (round log)		int	pine	ALF	Columns		**7x7x5**	**6**	**7**	**7**	**5.00**	60	123	7	7	123
Stewardship Garage (round log)		int	pine	ALF	truss parts upper cord		**7x7x37**	**5**	**7**	**7**	**37.00**	444	755	7	7	755
Stewardship Garage (round log)		int	pine	ALF	truss parts lower cord		**7x7x30**	**5**	**7**	**7**	**30.00**	360	613	7	7	613
Stewardship Garage (round log)		int	pine	ALF	truss vertical		**6x6x1**	**5**	**6**	**6**	**1.00**	12	15	6	6	15
Stewardship Garage (round log)		int	pine	ALF	truss vertical		**6x6x2**	**5**	**6**	**6**	**2.00**	24	30	6	6	30
Stewardship Garage (round log)		int	pine	ALF	truss vertical		**6x6x4**	**5**	**6**	**6**	**4.00**	48	60	6	6	60
Stewardship Garage (round log)		int	pine	ALF	roof purlin		**7x7x12**	**70**	**7**	**7**	**12.00**	144	3430	7	7	3430

Figure C.5: FSC Supplied Wood
Source: Courtesy of Boldt Construction

NATIONAL ASSOCIATION OF HOME BUILDERS

LOG HOMES

C O U N C I L

OR SHIPMENT TO:

CUSTOMER NAME	Aldo Leopold
ADDRESS	P.O. Box 77
	Baraboo, WI 53913
TELEPHONE NUMBER	(608) 355-0279

CERTIFICATE OF INSPECTION

The manufacturer certifies that each piece of timber covered by this certificate of inspection has been individually examined and inspected in accordance with the Grading Rules of the Log Homes Council and ASTM Standard D-3957, and that the timbers conform to the specifications as set forth below, being in good order and condition at the time of inspection.

The grade of each timber is identified by a mark on the End of the log. ORDER #: N/A

The grades are distinguished as follows:

BEAM GRADE	HEADER GRADE	WALL GRADE	UTILITY GRADE
Blue paint	Green Paint	Red Paint	Black Paint
NO. 1 SAWN ROUND TIMBER BEAM		NO. 2 SAWN ROUND TIMBER BEAM	
Orange Paint		Brown Paint	

SIZE	CLASSIFICATION	SPECIES	GRADE	LENGTHS	TOTAL FEET
8"	PURLIN-BEAM	RED PINE	#1	24'	24'
8"	PURLIN-BEAM	RED PINE	#1	29'	174'
8"	PURLIN-BEAM	RED PINE	#1	30'	390'
8"	PURLIN-BEAM	RED PINE	#1	37'	703'
8"x8"	BEAM	WHITE PINE	BEAM	12'	36'
8"x8"	BEAM	RED PINE	BEAM	16'	96'
8"x8"	BEAM	WHITE PINE	BEAM	16'	240'
8"x8"	BEAM	WHITE PINE	BEAM	10'	20'
8"x8"	BEAM	RED PINE	BEAM	13'	39'
8"x8"	BEAM	WHITE PINE	BEAM	13'	26'

CERTIFIED GRADER	CG ID NO.	DATE
[signature]	6603	7-27-06

White – Customer Copy Canary – Building Official Copy Pink – File Copy

Figure C.6: Log Grading Sheet (1 of 17)
Source: Courtesy of Boldt Construction

LAYLA QAROUT

EXPERIENCE

Zimmerman Architectural Studios
2015 – Present

INTERN ARCHITECT

Healthcare Design Studio. Engaged in the design process from design development to construction administration.

Kahler Slater
March – May 2015
Milwaukee, WI

INTERN ARCHITECT

Healthcare Design Studio.

UW-Milwaukee
2011 – 2015

ADJUNCT FACULTY/TEACHING ASSISTANT

Spring 2011: Design Studio; Arch 320 **(TA)**

Fall 2011: Design Studio; Arch 310 **(Adjunct Faculty)**

Spring 2012 - Fall 2012: Introduction to Building Technologies; Arch 210 **(TA)**

Spring 2013: Introduction to Architectural Theory; Arch 101 **(TA)**

Fall 2013: Introduction to Building Technologies; Arch 305 **(Adjunct Faculty)**

Spring 2014: Introduction to Architectural Theory; Arch 101 **(TA)**

Fall 2014: Introduction to Building Technologies; Arch 305 **(Adjunct Faculty)**

Peter Zumthor Workshop
Jericho, Palestine
July 2010

MODEL BUILDER

Hired by local firm - Habash & Associates - to build models of Peter Zumthor's design for the "House of Mosaics", and participate in workshop with Zumthor.

Birzeit University
West Bank, Palestine
2007 - 2010

INSTRUCTOR

Undergraduate design studios, architectural theory, computer-aided design, thesis chair/committee.

Saffarini & Associates
Ramallah, Palestine

ARCHITECTURAL DESIGNER

Project designer; schematic design of new civic projects and design competitions.

VOLUNTEERING

Women in Design Oct. 2016 – Present	**PLANNING COMMITTEE**
DOMKE Sept. 17 & 18, 2016	**DOORS OPEN MILWAUKEE - Volunteer** Annual event - 150 historic buildings open their doors to increase awareness to Milwaukee's history, architecture, and preservation of our built environment.
Speed Mentoring May 2016	**MENTORING YOUNG WOMEN LEADERS IN STEM**
Internship Taos, NM July – Aug 2014	**EARTHSHIP BIOTECTURE** 3 week long hands-on learning experience constructing an Earthship, while learning building concepts, designs, systems and techniques.
Habitat for Humanity Delaware March 2013	**UW-MILWAUKEE HABITAT FOR HUMANITY** Building construction during spring break.
Birzeit University West Bank, Palestine 2008 – 2009	**GRADUATION CEREMONY PLANNING COMMITTEE**

AWARDS & HONORS

Scholarship September 2015	**Jeffrey Cook Travel Scholarship Recipient To PLEA Conference**
Scholarship March 2015	**Jeffrey Cook SBSE Retreat Scholarship Recipient**

PROFESSIONAL ORGANIZATIONS

2016- Present	**American Institute of Architects – AIA Wisconsin**
2016- Present	**Building Technology Educators Society (BTES)**
2015- Present	**Society of Building Science Educators (SBSE)**

LANGUAGES

Arabic + English – Proficient, French – Working Proficiency

SKILLS

Design Proficient	**Sustainable Design, Architectural Design, Architectural Research, Graphic Design, Photography**
Software Proficient	**Autodesk Revit, AutoCAD, Adobe Suite, SketchUp, Climate Consultant, Autodesk Ecotect, COMFEN, DAYSIM**

EDUCATION

UW-Milwaukee — **PhD in Architecture – Sustainable Design**
2010 – 2017 (anticipated)

UW-Milwaukee — **Master of Architecture**
2004 – 2006

UW-Milwaukee — **Bachelor of Science in Architecture**
2001 – 2004

Birzeit University — **Architectural Engineering (Freshman Year)**
2000 - 2001
West Bank, Palestine

PUBLICATIONS

PLEA — **PASSIVE & LOW ENERGY ARCHITECTURE –Bologna, Italy**
September 2015
Utzinger, D. & Qarout, L. *"Reducing Environmental Impacts of Building Structures Through Local Material Sourcing & Processing."*

BTES — **POETICS + PRAGMATISM – Building Technology Educators' Society**
June 2017
Qarout, L. *"Integrating Pragmatism, Aesthetics and Ecology."* (Abstract accepted).

PRESENTATIONS

Women in Design — **CITIES & MEMORIES**
Milwaukee, WI
April 2016
"Ecology, Materials, and Memory."

ZAS — **ZIMMERMAN ARCHITECTURAL STUDIOS (ZAS)**
Milwaukee, WI
January 2016
"Reducing Environmental Impacts Of Building Structures Through Local Material Sourcing & Processing."

SBSE — **SOCIETY OF BUILDING SCIENCE EDUCATORS – ANNUAL CONFERENCE**
Highlands, NC
May 2015
"Embodied Energy and CO_2 Emissions Estimation of Building Structural Systems: A Case Study of the Aldo Leopold Legacy Center."

ALF — **ALDO LEOPOLD FOUNDATION (ALF)**
Baraboo, WI
January 2015
"Environmental Impacts of Building Materials: A Case Study of the Aldo Leopold Legacy Center."

USGBC Students — **MID-WEST REGIONAL SUSTAINABLE CONFERENCE**
Purdue University
March 2014
"Embodied Energy and CO_2 Emissions Estimation of Building Structural Systems: A Case Study of the Aldo Leopold Legacy Center."