Incorporating Life Cycle Assessment into the LEED Green Building Rating System

by

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Supervisory Committee

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Abstract

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Reused, recycled and regional product criteria within the LEED Green Building rating system are not based on comprehensive environmental assessments and do not ensure a measurable and consistent reduction of environmental burdens. A life cycle assessment (LCA) was conducted for the LEED-certified Medical Sciences Building at the University of Victoria to illustrate how LCA can be used to improve these criteria. It was found that a lack of public LCA data for building products, insufficient reporting transparency and inconsistent data collection methodologies prevent a full incorporation of LCA into LEED. At present, LCA data can be used to determine what building products are generally associated with the highest environmental burdens per unit cost and thus require separate LEED criteria. Provided its deficiencies are rectified in the future, LCA can be fully incorporated into LEED to design environmental burden-based criteria that ensure a measurable and consistent reduction of environmental burdens.

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List of Terminology

Acidification
The process by which chemical compounds are converted into acidic substances.

Base Case
A scenario in which no reused or recycled products are used.

Eco-label
A rating system that evaluates the environmental performance of a product and awards certification based on the degree of performance.

Environmental burden
A negative environmental impact.

Environmental burden-based criteria
LEED criteria that stipulate reductions of environmental burdens (e.g. 5% reduction of CO_2 emissions compared to status-quo practice)

Environmental performance
A term used to characterize the impact a product has on its environment. Low environmental performance is indicative of a product whose manufacture is associated with high environmental burdens. High environmental performance is indicative of a product whose manufacture is associated with low environmental burdens.

Eutrophication
An increase in chemical nutrients in an ecosystem resulting in excessive plant growth and decay, which decreases oxygen availability, decreases water quality and can threaten animal species.

Flow
Mass or energy exchange between unit processes or between a unit process and the environment.

Flow diagram
A visual representation of unit processes connected by flows.

ISO 14040
A standard that establishes guidelines and requirements for an LCA study.

LCI methodology
The process used to estimate environmental burdens based on established unit processes and flows.

LCA practitioner
Individual or group that conducts the life cycle assessment.

Life cycle stage
A portion of a product system consisting of unit processes and flows that interact to perform an aggregate function (e.g. raw material extraction, transportation, etc.).

L-level aggregation
An industry aggregation level consisting of 117 industries, established by the North American Industry Classification System.

Life cycle inventory
The phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle

Primary resource
A material that is taken from the environment and used in the manufacture of a product.

Primary energy resource
Primary resources that are used as or converted into fuels – namely coal, crude oil, hydropower, natural gas, and uranium oxide.

Product-based criteria
LEED criteria that stipulate direct requirement of building products (e.g. 5% of all products, by cost, must be made from recycled material).

Product system
A collection of unit processes connected by mass and energy flows which together perform one or more defined functions.

Rating system
A system used to assess the environmental performance of a product based on its adherence to an established set of performance criteria.

System boundary
Interface between a product system and the environment or other product systems.

Unit process
Smallest portion of a product system for which data are collected when performing a life cycle assessment.

Value
A specific reference to the monetary value of a product.

Abbreviations

AIE	Athena Impact Estimator
BEES	Building for Environmental and Economic Sustainability
CANSIM	CANadian Socioeconomic Information Management system
CIEEDAC	Canadian Industry Energy End-use Data Analysis Centre
CO_2e	Carbon dioxide equivalent
CPM	Centre for environmental assessment of Product and Material systems
ECGGS	Environment Canada Greenhouse Gas and Sinks report
EE	Embodied Energy
HHV	Higher Heating Value
I/O	Input/Output
ISO	International Standards Organization
LCI	Life Cycle Inventory
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LHV	Lower Heating Value
MRP	Material and Resources Performance
MSB	Medical Sciences Building
NAICS	North American Industry Classification System
NREL	National Renewable Energy Laboratory
OE	Operational Energy
PE	Primary Energy
PMR	Process-based Matrix Representation
PS	Process-based Sequential
PVC	Polyvinyl Chloride
StatsCan	Statistics Canada
USGBC	United States Green Building Council

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1 INTRODUCTION

1.1 A Brief History

Buildings provide a temperate and weatherized indoor environment in which we live, work, obtain medical services, attend events, and conduct myriad other activities. To serve these activities, a building must exchange mass and energy with the natural environment. Primary resources such as crude oil, limestone and iron ore must be extracted, refined and manufactured into products that form the structure, envelope, interior and mechanical systems of a building. Other primary resources such as natural gas and hydropower must be extracted and converted to provide space heating and electricity services. Water must be removed from lakes, rivers, and aquifers and then purified and pumped into the buildings for various purposes. Finally, the Earth's lands, waters, and atmosphere must absorb the solid, liquid and gaseous waste by-products of building activities. The proportion of total mass and energy flows in society allocated to buildings is substantial: According to the United States Green Building Council (USGBC), residential, commercial, and institutional buildings in the United States account for 70% of electricity usage, 39% of primary energy usage, 40% of raw material usage, 30% of waste output, and 12% of potable water consumption (USGBC, 2008).

Cumulative mass and energy flows between buildings and the environment have continually increased over history as building stocks have grown. The scale of such flows was introduced to public consciousness in the early 1970s due in large part to the Organization of Petroleum Exporting Countries (OPEC) oil embargo (Dong et al, 2005; Pierquet et al, 1998; USGBC, 2003). In 1973, both a temporary oil embargo of the United States and an increase in oil prices by OPEC-member countries threatened the availability of petroleum products in North America and led to rising petroleum product costs. In response, efforts were made to not only find alternative energy sources to reduce reliance on imported crude oil, but also to reduce demand by promoting energy conservation (Dong et al, 2005; Pierquet et al, 1998; USGBC, 2003). The heating and electricity requirements of buildings were largely provided by petroleum products at the time. Thus, buildings were ideal candidates for fossil fuel conservation strategies. Some strategies were based on voluntary acts, such as turning down thermostats at night, turning off lights when rooms were not at use and even shutting down buildings for days at a time (Sanborn Scott, 2007; USGBC, 2003). Other measures were directed towards technological innovations to building construction and operation, such as increased use of insulation, finer construction detail to reduce air infiltration, increased use of multi-pane windows and upgrades to more efficient heating systems (Dong et al, 2005; Pierquet et al, 1998, USGBC, 2003). These measures had considerable impact: In the 10 years following the OPEC oil embargo, residential energy consumption per household in the United States dropped by 31% (Pierquet et al, 1998).

Around the same period, the emerging field of environmental science was compiling evidence that linked environmental degradation to anthropogenic activity. Evidence first appeared in Rachel Carson's 1962 book Silent Spring, which drew attention to the environmental burdens of using DDT as a pesticide (Carson, 1962). Environmental science expanded throughout the 1970s to cover a broader range of environmental burdens including deforestation, loss of flora and fauna species, habitat and ecosystem preservation, air and water pollution, soil contamination and human health (Dersken and Gartrell, 1993).

Many environmental burdens were direct or indirect results of building construction and operation. Thus, buildings became target areas for improved environmental performance. Early examples included the elimination of lead-based paint in the late 1970s because of negative neurological impacts, the elimination of asbestos insulation in the early 1980s because of respiratory illness and the elimination of chlorofluorocarbon (CFC) as refrigerant fluid because of ozone depletion (CMHC, 1984; CMHC, 2006; EC, 2002). Also in the 1980s, two environmental burdens related to fossil fuel combustion were identified: the amplified greenhouse effect due to increased levels of carbon dioxide-equivalent gases (CO_2e) and the production of acid rain due to increased levels of sulphur dioxide gases in the atmosphere. Responses from the buildings sector included the further improvement of building envelope thermal efficiency and the conversion from higher-emission fuel oil to lower-emission natural gas heating systems (Pierquet et al, 1998; Sanborn Scott, 2007). In the 1990s, the intensity of both natural resource extraction and energy consumption for product manufacturing were reduced by the first widespread implementation of recycling and reuse programs for plastic, glass, metal and paper products in North America (Dersken and Gartrell, 1993). Within the building sector, this included not only the recycling and reuse of products used within the building (e.g. office paper, plastic bottles, etc.), but also the products used in building construction. Though steel had been recycled for some time, other building products such as concrete, asphalt, and gypsum drywall first incorporated recycled and reused material during this time (CMRA, 2008).

In the last decade, climate change has emerged as one of the most important environmental issues to date. Scientific evidence has linked the combustion of fossil fuels to an increase of atmospheric CO_2 gases from 280 parts per million (ppm) before the industrial revolution to 375 ppm in 2005, expected to increase to over 500 ppm by 2050 (IPCC, 2007). This increase is expected to have negative impacts on climate stability. Evidence has already linked the increase in CO_2 to an increase in the average surface temperature of the Earth with potential consequences ranging from rising sea levels, more extreme and variant weather patterns, increased droughts and floods, partial melting of polar regions, plant and animal species loss and decreased fresh water supply (IPCC, 2007). The need, then, to reduce anthropogenic dependence on fossil fuels is becoming increasingly important.

The need is especially important given the eventual decline of global crude oil availability. Virtually all anthropogenic activities require, whether directly or indirectly, some form of petroleum product derived from crude oil. Demand for petroleum products has grown and supply has decreased to such a point that the occurrence of "peak oil", the point at which the global extraction rate of crude oil is maximized, will occur sometime in the next 30 years (Smil, 2003). After this point, crude oil market availability will continually decline and prices will continually rise (Smil, 2003). Prices have already reached record levels, having more than quintupled between 1999 and 2007 (IEA, 2007). This price increase has, in turn, increased demand for and thus the cost of natural gas, the principal fuel used for space heating in North America. Natural gas prices have more than tripled in the U.S. between 1999 and 2007 (IEA, 2007). Considering the continued growth in building stock – 31% in residential and 28% in commercial/institutional floor space in Canada between 1990 and 2005 (OEE, 2005) – fuel prices are likely to continue increasing.

1.2 Modern Environmental Performance and Eco-labeling of Buildings

The principal strategy to reduce fossil fuel consumption in buildings is to improve energy efficiency in areas of heating and electricity. Many provincial and federal government programs and incentives exist in Canada to achieve such reductions. A sample of these is listed in Table B1 of Appendix B.

The first three entries in Table B1, namely EnergyStar, R-2000 and EnerGuide, are listed as 'eco-labels'. Eco-labels certify a product based on varying scopes of environmental performance and are used to stimulate market demand for environmentally benign products. There are existing eco-labels for both specific aspects of building operation and specific building products and assemblies. There are also eco-labels for the overall environmental performance of a building. The numerous types of environmental performance criteria considered within eco-labels are summarized in Table B2 of Appendix B.

Eco-labels for buildings are based on point allocation, where points are awarded for adherence to specific environmental performance criteria. Certification is then based on a total point score. The most widely-used eco-label for buildings is the Leadership in Energy and Environmental Design (LEED) rating system. Though LEED has proven successful in creating market demand for environmentally benign building design, its criteria pertaining to the use of reused, recycled and regionally manufactured products are not based on comprehensive environmental assessments. As such, the reduction of environmental burdens is not always ensured through adherence to these criteria. Criteria deficiencies include the following:

- Criteria are cost-based (e.g. reuse of 10% of total products, by cost) and often do not adequately correlate to the environmental performance of building products
- Criteria often award points for status-quo practices
- Criteria are based on the total value of products (e.g. recycling of 10% of total products, by cost) and do not account for the varying environmental performance of different products
- Criteria do not ensure a consistent reduction of any specific environmental burden (e.g. 5% reduction in crude oil consumption)
- Criteria are immutable and are often not appropriate in all geographical regions
- Criteria may promote the reduction of some environmental burdens but may promote the increase of others

1.3 Life Cycle Assessment as a Solution

Reused, recycled and regional product criteria can be improved through the incorporation of life cycle assessment (LCA). LCA is used to estimate the environmental burdens of a manufactured product by quantifying mass and energy flows over the product’s life cycle (resource extraction, product manufacturing, product use, product disposal and intermediate transportation) (ISO, 1997). Examples of environmental burdens quantified through LCA include global warming potential, ozone depletion, acidification, eutrophication and natural resource depletion (ISO, 1997).

Though capable of providing a systematic and comprehensive environmental assessment of a building, LCA is presently hindered by several deficiencies. First, performing an LCA is costly and time consuming, thus LCA data only exist for a select number of products. Second, LCA is highly subjective in that decisions made and methodologies used by the individual conducting the LCA have substantial impact on results. Impact is particularly substantial when selecting the life cycle inventory (LCI) methodology. Third, LCA results are subject to regional, temporal and technological variance in data. Given these deficiencies, it is often difficult to obtain LCI data for a product and to compare the environmental performance of different products. Transparency in study methodology, then, is crucial to allow some degree of comparison.

Provided the data is accurate, then LCA results for building products can be incorporated into LEED reused, recycled and regional product criteria to ensure a more consistent reduction of environmental burdens. Several methods of incorporation include the following:

- Increase percentage requirements (e.g. 5% to 10%) within select criteria to promote a greater reduction of environmental burdens in general,
- Develop criteria that reward the selection of building products of high environmental performance,
- Develop individual criterion for building products that are associated with the highest environmental burdens (e.g. mandatory recycling of 10% of concrete), and;
- Replace *product-based criteria* (i.e. criteria that stipulate percentage requirements for products) for *environmental burden-based criteria* (i.e. criteria that stipulate percentage reductions of specific environmental burdens)

1.4 Thesis Objective

The objective of this thesis is to explore both the benefits and obstacles of LCA incorporation into LEED. Specific goals include the following:

1.4.1 Assess the Current State of LCI Data

Critical to the incorporation of LCA into LEED is a comprehensive, publicly available LCI database developed using standardized data collection methodologies. The availability and degree of reporting transparency in public LCI data applicable to Canada are assessed by conducting an LCA on a case study building. The building selected for analysis is the Medical Sciences Building (MSB) at the University of Victoria.

1.4.2 Compare LCI Methodologies

The selection of a particular LCI methodology will impact LCA results. Therefore, the development of a standardized data collection procedure must specify one type of LCI methodology to be used. The need for such a standard methodology will be illustrated by comparing environmental burdens quantified through three LCI methodologies – process-based sequential representation (PS), process-based matrix representation (PMR), and input-output-based matrix representation (I/O).

1.4.3 Assess the Efficacy of LEED criteria

Specific MSB building products are selected to meet the reused, recycled and regional product criteria. These selections result in a specific reduction of environmental burdens, which are quantified using LCA. Product selection scenarios are then modeled that maximize and minimize the reduction of environmental burdens based on a constant total value of reused and recycled products. The extent to which environmental burdens are increased or decreased in these scenarios is quantified and discussed.

1.4.4 Explore Environmental Burden-based Criteria

The replacement of product-based criteria with environmental burden-based criteria ensures a measurable and consistent reduction of specific environmental burdens. The benefits of and difficulties in developing such criteria are discussed.

1.5 Chapter Outline

In Chapter 2, the fundamental components of LCA and its application to the building sector are described. First, the definition, purpose, principles and framework of LCA are presented. The ISO standard 14040 for conducting an LCA is then reviewed. Next, the three types of LCI methodologies subject to analysis in this study are introduced and their mathematical frameworks are described. Finally, the application of LCA to buildings is discussed and a literature review on related studies is presented.

In Chapter 3, environmental performance rating systems (eco-labels in particular) are reviewed and the methodologies in which they rate the environmental performance of a building are described. Summaries of popular rating systems for buildings used within North America, most notably LEED, are provided. The deficiencies of several LEED criteria and the ways in which LCA may improve the criteria are then described.

In Chapter 4, the goal and scope of this study are defined and the data for each LCI methodology are developed. First, the purpose of the study and its intended audience are defined. System boundaries for the study are then established and data collection methodologies are described for both the selection of building products and the development of LCI data. Missing and inadequate data are identified and methodologies used to address such data are described. Finally, building product quantity and cost data and LCI data for each methodology are presented.

In Chapter 5, results from the three LCI methodologies are presented and the most qualified methodology is selected for further use in this study. This LCI methodology is used to calculate the environmental burdens per unit floor area and the ratios of embodied to annual operational environmental burdens. Results are compared to those found in similar studies. Finally, environmental burdens are allocated to individual products and assemblies in the MSB.

In Chapter 6, PMR-based LCI data are used to assess the efficacy of LEED reused, recycled and regional product criteria in promoting a consistent reduction of environmental burdens. Summaries are given and LCI data are developed for reused and recycled products in the MSB. Reductions of environmental burdens due to the use of reused and recycled products are then quantified. Product selection scenarios are then modeled that maximize and minimize the reduction of environmental burdens based on a constant total value of reused and recycled products. Due to a lack of available transport data, reductions of environmental burdens due to the use of regional products could not be quantified. Instead, general transport requirements for each product in the MSB are rated.

In Chapter 7, study results obtained in Chapter 5 and 6 are discussed. First, the state of public LCI data applicable to Canada is discussed. Next, the benefits and drawbacks of the three LCI methodologies and the difficulties in developing LCI data in general are discussed. Next, the efficacy of LEED reused, recycled and regional product criteria in promoting a consistent reduction of environmental burdens is discussed. Finally, modifications to current criteria are proposed and environmental burden-based criteria that stipulate overall reductions of environmental burdens based on LCA results are explored.

In Chapter 8, study objectives and methods are reviewed, key findings are summarized and recommendations for future work are identified.

2 A REVIEW OF LIFE CYCLE ASSESSMENT

In this chapter, the fundamental components of LCA and its application to buildings are described. First, the definition, purpose, principles and framework of LCA are presented. The ISO standard 14040, established to ensure a consistent and transparent LCA study methodology, is then reviewed. Next, the three types of LCI methodologies subject to analysis in this thesis are introduced and their mathematical frameworks are described. Finally, the application of LCA to buildings is discussed and a literature review on related studies is presented.

2.1 Introduction

Life cycle assessment (LCA) is a method used to estimate the environmental burdens associated with a manufactured product. Mass and energy flows are compiled over a product's life cycle which consists of several life cycle stages: raw material extraction, product manufacturing, product use, product disposal/reuse/recycling and intermediate transportation (ISO, 1997). Environmental burdens are estimated based on the quantities and types of cumulated mass and energy flows. LCA is used exclusively to estimate global or regional environmental burdens that can be directly attributed to measurable mass and energy flows. Examples include global warming potential, ozone depletion, acidification, eutrophication and natural resource depletion (ISO, 1997). Local environmental burdens or those not directly attributable to measureable mass and energy flows, such as soil erosion or species extinction, cannot be assessed within the framework of LCA.

LCA is used by government and non-government organizations to make environmentally-informed decisions. Applications of LCA include strategic planning, improved product and process design, marketing of more sustainable products, environmental impact assessments and development of environmental taxes (Jensen et al., 1997). LCA databases are well-developed for several products including plastics, metals, various wood products, primary energy resources and energy carriers (e.g. gasoline, electricity, etc.). LCA databases are somewhat developed for rubber products, agricultural products, and non-metallic mineral resources and products. Both national and international organizations have established LCA databases and related software, several of which include data for hundreds of products (Curran and Notten, 2006).

The life cycle of a product is modeled using a *product system* (see Figure 2.1). The product system is contained by the *system boundary* – the "interface between the product system and the environment or other product systems" (ISO, 1997). Within the system boundary are the *life cycle stages* of the product (e.g. raw material extraction, transportation, etc.). Mass and energy flows exist either as *elementary flows, boundary product flows or intermediate product flows*. Elementary flows connect the product system to the environment and have not been (in the case of inputs) or will not be (in the case of outputs) transformed by anthropogenic activities (ISO, 1997). Examples include inputs of crude oil or outputs of CO_2e emissions. Boundary product flows connect two product systems whereas intermediate product flows are contained within a single product system (ISO, 1998). Examples include rubber and diesel.

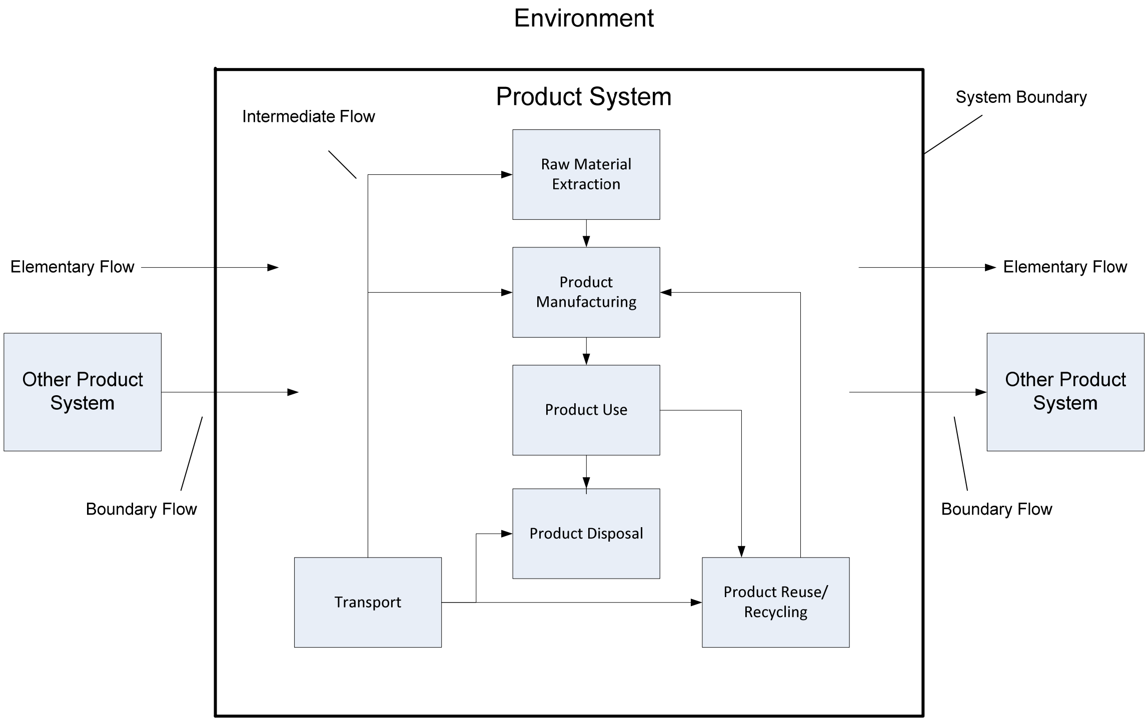

Figure 2.1: Schematic of Product System, adopted from ISO 14040 (ISO, 1998)

Each life cycle stage consists of one or several *unit processes* – the "smallest portion[s] of a product system for which data [are] collected" (ISO, 1997). Flows connected to unit processes include natural resources, manufactured products and waste products. Inputs and outputs to a unit process are balanced based on conservation of energy and mass (ISO, 1997). Examples of unit processes include aluminum smelting or natural gas combustion. The interaction between unit processes and flows is illustrated in a *flow diagram*. A simplified flow diagram for the use of steel beams in the structure of a building is shown in Figure 2.2. Interactions between unit processes in Figure 2.2 are illustrative and do not necessarily reflect actual steel beam manufacture.

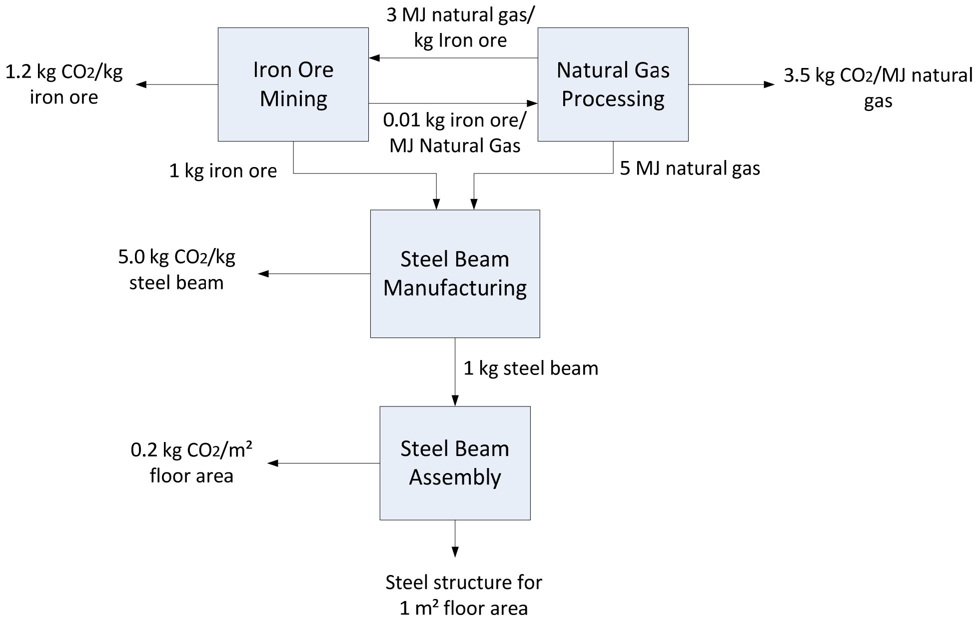

Figure 2.2 Simplified Flow Diagram for Steel Beam Product System

2.2 Methodological Framework

ISO Standard 14040 – Life Cycle Assessment: Principles and Framework was established in 1997 to provide clear guidelines and requirements for an LCA study. Such guidelines and requirements address the subjective nature of LCA in which decisions and assumptions made by each individual *LCA practitioner* have crucial influence on results. Adherence to ISO 14040 helps ensure a consistent methodological approach with sufficient transparency and clarity such that LCA results not only are properly interpreted but are also repeatable (ISO, 1998).

ISO 14040 separates an LCA study into four phases: goal and scope, inventory analysis, impact assessment and interpretation. The purpose of and guidelines for each phase are described in Sections 2.2.1 to 2.2.4.

2.2.1 Goal and Scope

The goal describes, “the intended application, the reasons for carrying out the study and the intended audience” (ISO, 1997). The scope defines the LCA study methodology based on three parameters: the system boundary, the functional unit and data quality.

2.2.1.1 System Boundary

The compilation of all possible unit processes and flows for a product is time-consuming. Therefore, ISO 14040 states that “resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study” (ISO, 1998). It is recommended in ISO 14040 that criteria for the exclusion of unit processes, flows, or life cycle stages are based on mass, energy, or environmental burden thresholds (e.g. excluding input flows that constitute less than 1% of total mass input to a unit process or excluding outputs to the environment that have no global warming potential). Having established the system boundary, the practitioner must ensure that “the criteria and the assumptions on which [the system boundary is] established [are] clearly described” and that “any decision to omit life cycle stages, processes or inputs/outputs [are] clearly stated and justified” (ISO, 1998).

2.2.1.2 Functional Unit

A product has one or more functions. A function of an office building, for example, is to provide working space for employees. A function is quantified by the *functional unit* – a reference unit by which the mass and energy flows within a product system are normalized (ISO, 1998). For example, if the function of providing heat is compared between two heating systems, then an appropriate functional unit may be the heat energy required to maintain a unit volume of interior space at a given temperature for a given period of time. Flows within the product system are then normalized to the functional unit, allowing easy comparison between products of similar function.

2.2.1.3 Data Quality

Estimations of environmental burdens depend entirely on the data that quantify flows between unit processes. The data, however, are subject to temporal, geographical, and technological variations (ISO, 1998). The progression of time leads to improvements in process technologies and changes in environmental standards for industry. Each geographical region has specific characteristics, such as the mix of primary energy resources used to generate heat and electricity, sophistication of technologies, environmental standards for industry and travel distances for raw materials and products. Finally, the type of technology on which data are based (e.g. the most efficient, the most common, an average of available technologies, etc.) will also influence the data (ISO, 1998).

Given this influence, ISO 14040 requires that the quality of data needed to meet the goal of the study be stipulated in terms of time period, geography and technology (e.g. data must be within the years 1990 and 2000, specific to British Columbia and based on the most efficient of available technologies). Such stipulations are necessary so the reader can "understand the reliability of the study results and properly interpret the outcome of the study" (ISO, 1998).

2.2.2 Life Cycle Inventory

In the life cycle inventory (LCI) phase, mass and energy flows are compiled for each unit process within the system boundary. ISO 14040 recommends several steps which are to be taken within this phase, "to ensure uniform and consistent understanding of the product systems to be modeled" (ISO, 1998). These steps include:

- Drawing of specific flow diagrams that detail all unit processes
- Description of each unit process and associated data quality
- Listing of all units of measurement
- Description of data collection and calculation techniques
- Instructions pertaining to any special cases or irregularities associated with data

(ISO, 1998)

These recommendations apply whether data are directly measured, estimated, or referenced from existing literature or databases (ISO, 1998). If adequate descriptions of data are not permitted due to confidentiality arrangements, such restrictions must be made clear (ISO, 1998).

The availability of data may often be limited due to missing or inadequate data that fail to meet the scope of the study (i.e. data are temporally, geographically or technologically inapplicable). When missing or inadequate data are identified, the practitioner may, in their place, develop appropriate estimations or take data from the literature for the same or similar process (ISO, 1998). Alternate data sources may include industrial end-use statistics which compile annual data on product output, energy consumption and key environmental burdens for a range of energy, mining, agriculture, forestry and manufacturing industries (Yohanis and Norton, 2002). Such data, however, are based on surveys which do not specify the processes included in the reporting (e.g. vehicle fleet fuel usage, heating of administrative buildings, etc.).

Data estimation and substitution, of course, lead to a degree of error and uncertainty in LCA results. Given no established uncertainty analysis component to LCA, it is critical that the treatment of missing or inadequate data are clearly documented (ISO, 1998).

All energy flows must be quantified in terms of *primary energy* which accounts for "the production and delivery of fuels, feedstock energy and process energy" (ISO, 1998). Feedstock energy is the heat of combustion of a raw material not used as an energy source (e.g. crude oil derivatives in plastic). The quantification of electricity flows, in particular, must take into account the "production mix and the efficiencies of combustion, conversion, transmission and distribution" (ISO, 1998). Energy content of combustible fuels can be expressed either as the higher heating value (HHV) (heat produced from complete combustion of fuel) or the lower heating value (LHV) (heat produced from complete combustion minus heat required to evaporate embedded water in fuel). The choice of HHV or LHV must be stated and applied consistently throughout the study (ISO, 1998).

Unit processes will often output more than one product. Thus, the environmental burdens associated with the unit process must be allocated to each of its products. Allocation procedures must be clearly documented (ISO, 1998).

2.2.3 Impact Assessment

In the impact assessment phase, environmental burdens of the product system are estimated based on the quantity and types of mass and energy flows calculated in the inventory analysis (ISO, 1997). The methodology by which each environmental burden is estimated must be documented (ISO, 1997).

2.2.4 Interpretation

In the interpretation phase, conclusions are drawn and recommendations made based on the results of the impact assessment and/or the inventory analysis (ISO, 1997). Conclusions and recommendations are consistent with the goal and scope of the study (ISO, 1997). Any sensitivity analyses performed on the data are included in this phase (ISO, 1997).

2.3 LCI Methodologies

There are several types of LCI methodologies available to the practitioner, each unique in terms of data sources, time and resource requirements and data results. *Process-based* LCI is the most common methodology and consists of two types: *process-based sequential* (PS) and *process-based matrix representations* (PMR*). Economic input-output* (I/O) based LCI is less common. Hybrid-based LCI is the least common and combines features of both process-based and I/O-based methodologies. Estimations of environmental burdens can vary significantly depending on which methodology is used. Therefore, "the models used [to represent the product system] should be described and the assumptions underlying those choices should be identified" (ISO, 1998).

Descriptions of PS, PMR, and I/O-based methodologies are provided in this section. A description of hybrid-based LCI is not provided in this study but can be found in the literature (Treloar, 1997; Suh and Huppes, 2005)

2.3.1 Process-Based Sequential LCI

In PS-based LCI, physical units of measure are used in the quantification of flows and environmental burdens. The principal tool is the flow diagram which illustrates the relationship between unit processes and flows within a product system. Consider the flow diagram for steel beams in Figure 2.2. The functional unit is identified as 1 m^2 of floor area. Total CO_2 emissions attributable to the manufacture and assembly of the steel beam are calculated by the summation of the emission factors for each unit process.

The principal drawback to PS-based LCI is its inconsistent accounting of unit processes (Suh and Huppes, 2005). In Figure 2.2, for example, the product system is modeled by what can be called a *one-tiered analysis* – the inclusion of unit processes whose outputs are used directly in the manufacturing or transport of the final product. A *two-tiered analysis* expands the system boundary 'upstream' to include unit processes whose outputs serve as inputs to tier one unit processes. A two-tier analysis is shown in Figure 2.3. Interactions between unit processes do not necessarily reflect actual steel beam manufacture. A *three-tiered analysis* expands the system boundary further upstream to include inputs to tier two unit processes, and so forth. With each tier added, additional environmental burdens are attributed to the structural steel product system. These additional burdens become gradually smaller as the cumulative total converges.

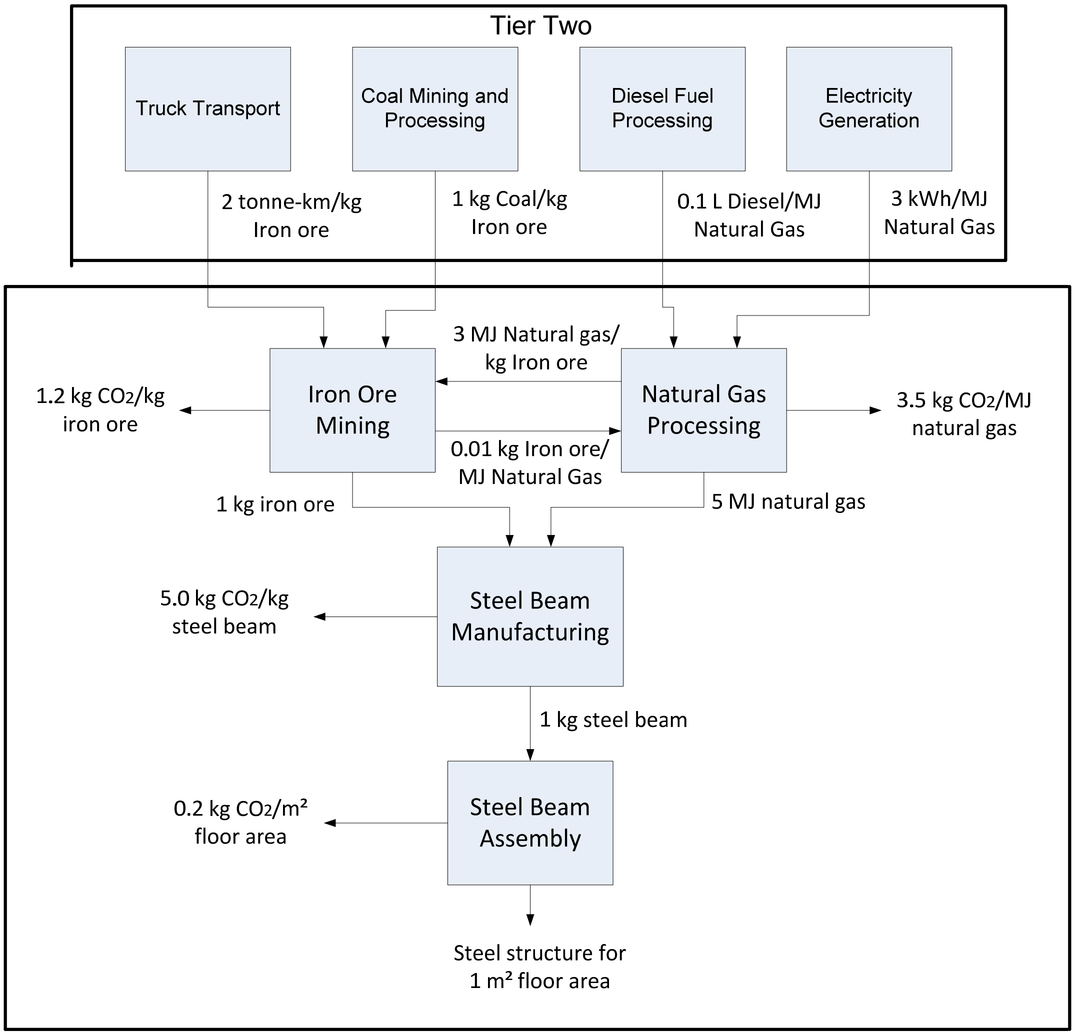

Figure 2.3: Simplified Steel Beam Product System, Two-tier Analysis

PS-based LCI, then, is not consistent in its account of upstream flows. Nor is it consistent in its account of *product loops*, which occur when a product becomes an indirect input into its own production. In Figure 2.3, for example, the mining of iron ore requires the input of natural gas, the processing of which requires the input of iron ore, the mining of which requires the input of natural gas, and so forth. The practitioner must decide how many times to repeat the loop or use a convergence formula to account for total environmental burdens (Suh and Huppes, 2005).

2.3.2 Process-Based Matrix Representation

In PMR-based LCI, *all* upstream unit processes and product loops are accounted by relating unit processes and flows through a system of simultaneous linear equations. These equations are modeled in a $n \times n$ *product system matrix* A = $|a_{ij}|$ which lists products along the rows and unit processes along the columns. An entry in row *i* and column *j* (i.e. a_{ij}) represents the input or output of product *i* corresponding to process *j*. Inputs and outputs are noted by negative and positive values, respectively. It is assumed that the product system operates in steady state condition (i.e. the interactions between unit processes do not change). A matrix representation of the steel beam product system in Figure 2.2 and example calculations of methodologies defined in this section are found in Appendix A.

The products from a unit process may be used as inputs to another unit process in the product system or they may exit the product system and be delivered, for example, to the final consumer. These two scenarios are represented by Equation 2.1 which is rearranged in Equation 2.2.

$$Ax = y \qquad (2.1)$$

$$x = A^{-1}y \qquad (2.2)$$

where: *A* is the product system matrix

x is the column vector representing the total product output from each unit process

y is the column vector representing the product output from each unit process that exit the product system

Thus, the total output from each unit process is calculated by specifying the products that exit the product system.

Environmental burdens are associated to each unit process by defining an $m \times n$ *environmental burden matrix* B=$|b_{ij}|$ where an entry in row *i* and column *j* represents the environmental burden *i* related to unit process *j*. The total environmental burdens of the product system are calculated by multiplying the environmental burden of each unit process by its total product output, and summing the results:

$$E = Bx = BA^{-1}y \qquad (2.3)$$

where: *E* is the column vector representing total environmental burdens
B is the environmental burden matrix

Estimations of total environmental burdens are more accurate in PMR than PS-based LCI, where the latter typically accounts for only a select number of upstream processes. Further, the product system matrix is not restricted to a single product system, but can be easily expanded to include an indefinite number of product systems and theoretically an entire economy.

2.3.3 Economic Input-Output

I/O-based LCI uses monetary units of measure in the quantification of product flows. The principal component of I/O-based LCI is the national input-output table which models a national economy as monetary flows between aggregated industries (Leontief, 1936). An input-output table representing the steel beam product system in Figure 2.2 and example calculations of methodologies defined in this section are found in Appendix A.

In I/O-based LCI, input-output tables are converted to an $n \times n$ *industry-industry matrix* C = |c_{ij}| which lists in row *i* and column *j* the monetary input from industry *i* needed to produce one unit of monetary output in industry *j*. All entries in the matrix are positive. Monetary outputs from each industry will be, in part, consumed by other industries within the economy and, in part, delivered to the consumer. This is modeled in Equation 2.4 and rearranged in Equation 2.5.

$$s = Cs + t \qquad (2.4)$$

$$s = (I - C)^{-1}t \qquad (2.5)$$

where: *C* is the industry-industry matrix
s is the column vector representing the total output from each industry

t is the column vector representing output from each industry delivered to the consumer
I is the identity matrix

Thus, the total output from each industry is calculated by specifying the output from each industry delivered to the final consumer.

Environmental burdens are attributed to each industry by defining a $m \times n$ matrix D=|d_{ij}| where entry d_{ij} represents the environmental burden *i* related to the unit monetary output of industry *j*. The total environmental burdens of the economy are calculated by multiplying the environmental burden of each industry by its total output and summing the results:

$$F = Ds = D(I - C)^{-1} t \qquad (2.6)$$

where: F is the column vector representing total environmental burdens of the economy
D is the environmental burden matrix

The system boundary of I/O-based LCI is more complete than process-based LCI since *all* economic interactions within an economy are accounted (e.g. heating and lighting of administrative buildings, fuel purchases, wages, etc.). Process-based LCI, on the other hand, accounts for a select number of unit processes which model only the major mass and energy flows within a product system. Further, I/O-based LCI is less time-consuming than process-based LCI since I/O data are compiled by national governments and not the practitioner. I/O-based LCI results are, however, less accurate than process-based LCI for several reasons:

- Industry classifications are highly aggregated. Thus, I/O-based LCI provides representative results only when the production technology of a given product closely resembles that of the aggregate industry to which the product belongs.
- Monetary units do not always convert to physical units by the same ratio due to variations in technology, inflation, and taxation.

- The compilation of national I/O tables takes several years, during which time the conversion between monetary and physical units will change. I/O data, then, are always outdated to some extent.
- Data are averaged nationally and do not account for regional technologies and economies.
- Environmental burden data may not be available for some industries. Where data exist, inconsistencies within the scope of environmental indicators included, time of data collection and industry classification may lead to misrepresentative results.
- Import products are assumed to be manufactured under the same conditions as domestic products, which is not always the case. Industries that rely heavily on imports, then, will generally be misrepresented in I/O tables.
- The product use stage cannot be modeled using I/O-based LCI but must rather be modeled using another methodology.

(Joshi, 2000; Suh and Huppes, 2005)

I/O-based LCI, then, is used only when a very general and relatively quick assessment of environmental burdens is required. Where more detailed or comparative analyses are required, process-based LCI should be used (Joshi, 2000; Suh and Huppes, 2005).

2.4 LCA and Buildings

2.4.1 Introduction

LCA can be applied to a single product or to an assembly of products, such as a building. A typical life cycle of a building can be broken into three distinct phases each consisting of one or several life cycle stages, as illustrated in Figure 2.4. The assembly phase refers to the collection of raw materials through resource extraction or recycling, the manufacture of these raw materials into products, the assembly of products into a building, the replacement of building products and assemblies, and intermediate transportation. The operation phase refers to heating and electricity requirements, water services and other services excluding material replacement. The disassembly phase refers to the decommissioning and demolition of the building, the disposal/recycling/reuse of building products and assemblies, and intermediate transportation steps. Each life cycle stage can consist of many unit processes. Several of these are listed in Table A8 in Appendix A.

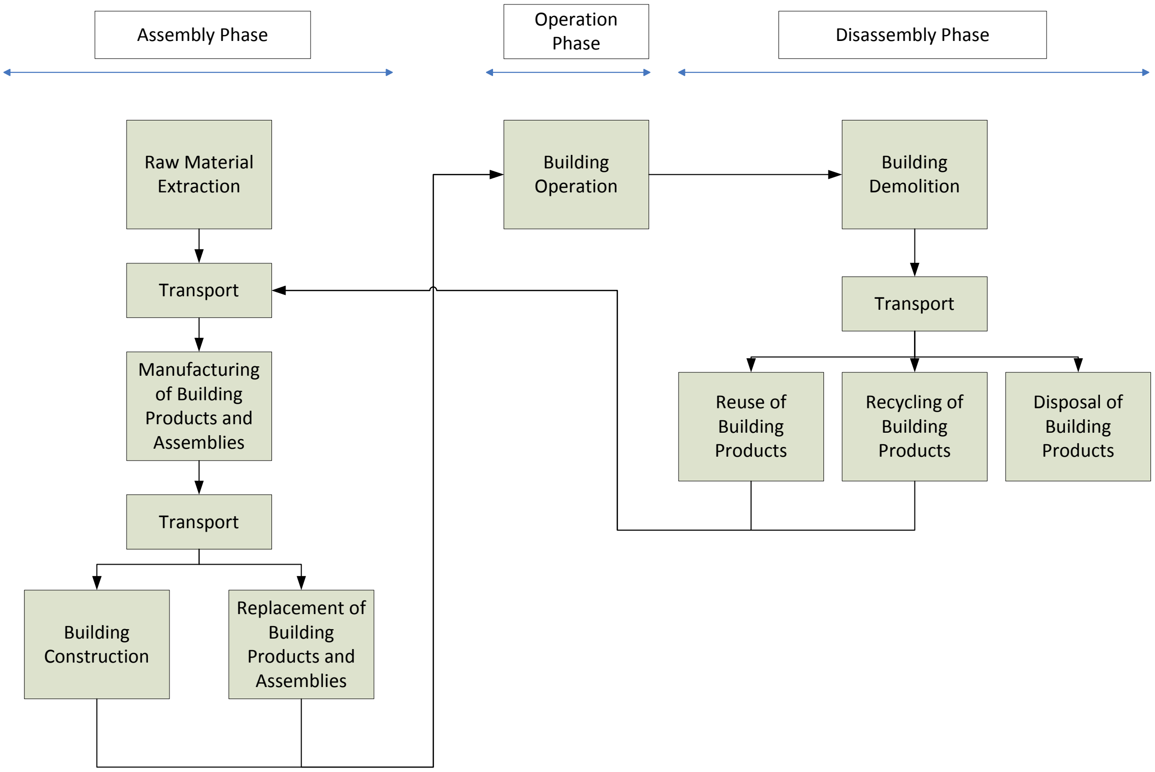

Figure 2.4: Life Cycle of a Building

2.4.2 Literature Review

20 LCA studies on buildings were found in the literature. Geographical ranges include Canada, United States, Sweden, Finland, Spain, UK, Australia, New Zealand, Japan, and China. Dates of publications range from 1996 to 2007. The goal of each study varied, though all investigated the *life cycle energy* of a building. Life cycle energy can be partitioned according to each building phase:

1) Embodied energy (EE)– the cumulative energy consumed in the assembly phase
2) Operation energy (OE)– the cumulative energy consumed in the operation phase
3) Disposal energy – the cumulative energy consumed in the disassembly phase

Energy efficiency programs and incentives In Canada summarized in Table B1 of Appendix B address only reductions of OE. Such reductions, however, result in increases in EE due to the use of additional insulation, the use of higher insulating materials, improved construction workmanship or the use of more sophisticated technologies. Thus it is important to consider both types of energy when addressing the energy efficiency of a building. Table 2.1 illustrates this importance by relating EE and OE from several LCA studies as percentages of life cycle energy. In the final column, EE is expressed as the equivalent years of OE.

Table 2.1: Literature Review, Embodied to Annual Operational Energy Ratio

Author	**Building Life (Years)**	**Embodied Energy (%)**	**Total Operational Energy (%)**	**Embodied to Annual Operational Energy Ratio**
Blanchard and Reppe, 1998	50	6.1[1]	93.7[2]	3.3
Cole, 1996	50	11-18	82-89	6.2-10.9
Fay, 2000	25 50 75 100	39 31 28 25	61 69 72 75	16.0 22.5 29.1 33.3
Kotaji et al, 2003	Not given	10-20	80-90	N/A
Li, 2006	35	7.8-18.8[1]	71.2-92.2	3.0-9.2
Scheuer et al, 2002	75	2	98	1.5
Thormark, 2002	50	40	60	33.3
Yohanis and Norton, 2002	25 50 100	51 45 42	49 55 58	26 40.9 72.4

1 – replacement of building products and assemblies not included
2 – embodied energy of replacement material included as operational energy
- Disposal energies are negligible in all cases
- Heating and electricity requirements and material replacement schedules are assumed constant

EE ranges between 1.5 and 72.4 years of OE. There are many factors influencing this relation:

- OE efficiency – an OE-efficient building has higher EE and lower OE than a typical building
- Building Life – an increased building life span requires increased material replacements thus higher EE
- Climate – buildings in colder climates have greater heating requirements thus higher OE
- Occupancy – a high-occupancy building has greater electricity requirements and thus higher OE
- Regional Fuel Mix – primary energy resources used for heating, electricity generation and industrial process fuels each have a specific EE
- Recycled material content – a higher recycled content in building materials reduces EE
- Material replacement schedules – more frequent material replacements increase EE

- Transport distance – larger distances between production facilities and building sites increase EE

The system boundary and data sources particular to each LCA may substantially influence the relation between OE and EE. Proper interpretation of the data in Table 2.1 requires sufficient documentation of the system boundaries and study methodologies in each LCA. Thus, the literature was reviewed based on the inclusion of the following ISO 14040 requirements:

1) List of life cycle stages
2) List of unit processes included in each life cycle stage
3) Statement of functional unit
4) Referencing of data sources
5) Discussion of data quality (some reference to temporal, geographical, and technological applicability of data to the study)
6) Statement of primary energy consideration for building operational energy
7) Indication of HHV or LHV where energy data are presented

Table A9 in the Appendix details the results of the analysis particular to each LCA. The key findings are summarized below:

1) Statement of life cycle stages – 60% of the studies do not clearly indicate which life cycle stages are included within the system boundary. 25% of the studies do not clearly indicate the inclusion/exclusion of four or more life cycle stages. 10% do not clearly indicate the inclusion/exclusion of any life cycle stage.
2) List of unit processes – 85% of the studies do not identify the unit processes included for each life cycle stage
3) LCI Methodology – 78% of the studies do not state which specific LCI methodology is used.
4) Statement of functional unit – 84% of the studies do not make a clear statement of the functional unit. However, the functional unit can usually be inferred.
5) Data sources referenced - 20% of the studies do not specifically reference the source from which data were obtained.

6) Data quality discussed - 60% of the studies do not comment on either the temporal, geographical or technological applicability of data used.
7) Primary energy specified - 65% of the studies do not specify primary energy considerations for fossil fuels or electricity used in the operational phase of a building.
8) HHV or LHV of fuel specified – 83% of the studies do not indicate the use of HHV or LHV when energy units are expressed.

It is concluded that existing LCA studies on buildings do not provide adequately transparent documentation of system boundaries and study methodologies. Of course, the majority of the reviewed studies are LCA reports that have been condensed for journal submission. ISO 14040 does not explicitly address transparency requirements when LCA studies are condensed into journal form. However, one or two paragraphs briefly outlining the key decisions and assumptions made by the practitioner would greatly assist the reader in properly interpreting the results.

2.4.3 LCA Software Tools for Buildings

There are many LCA software tools that estimate the life cycle environmental burdens of a building. A comprehensive online database of such software tools has been compiled by the International Initiative for a Sustainable Built Environment (iiSBE) (SBIS, 2008). The building products and environmental burdens considered vary between each software tool. There are two software tools whose data apply to North America: Building for Environmental and Economic Sustainability (BEES) and the Athena Impact Estimator (AIE). BEES is developed by the National Institute of Standards and Technology and uses U.S-based LCI data for 230 building products (Lippiatt, 2007). AIE is developed by the Athena Sustainable Materials Institute and uses both Canadian and U.S.-based LCI data for 84 building products (ASMI, 2008).

Similar to individual LCA reports, LCA software tools should provide sufficient documentation that describes system boundaries and data collection methodologies. The BEES technical manual provides excellent documentation. The AIE does not have such a manual. Rather, documentation is found within individual building product LCI reports written by various organizations. Athena research guidelines outline documentation requirements for the LCI reports (ASMI, 1997); however, these guidelines are not always followed. Several LCI reports provide insufficient documentation, including the failure to state life cycle stages, list criteria for the inclusion of unit processes, illustrate process-flow diagrams and describe data quality.

Neither software tool explicitly states the LCI methodology being used, though it is clear that either PS or PMR-based LCI is employed. Through personal communication with an ASMI representative, it was learned that the AIE uses primarily PS-based LCI, though PMR is occasionally used for some products (Meil, 2008). The particular products modeled with PMR-based LCI were not identified.

Therefore, similar to the literature, inadequate transparency is evident in LCA software tools, at least within North America. BEES lacks only a clear statement of LCI methodology, while AIE lacks sufficient documentation in several areas. Thus, LCA results calculated by AIE in particular will be difficult to interpret and reproduce.

2.5 Summary

LCA is applied to buildings principally to estimate life cycle primary energy consumption and CO_2e emissions. LCA databases and software tools for buildings have proliferated in recent years. ISO 14040 guidelines and requirements of an LCA study, established to address the subjective nature of LCA, were reviewed in this Chapter. Such guidelines and requirements, however, are rarely followed in the LCA studies and software for buildings reviewed by this author.

3 RATING SYSTEMS AND LCA

LCA results are often incorporated into rating systems that rate a product based on its adherence to an established set of environmental performance criteria. In this Chapter, ratings systems are defined and the methodologies in which they rate the environmental performance of a building are described. Summaries of popular rating systems for buildings used within North America, most notably LEED, are then provided. Finally, the deficiencies of several LEED criteria and the ways in which LCA may improve the criteria are described.

3.1 Rating Systems and Eco-labels

A rating system assesses the environmental performance of a product based on its adherence to an established set of environmental performance criteria (herein referred to in this Chapter as 'criteria'). Rating systems are used both to assess the environmental burdens attributed to a single product and to compare the environmental performance between different products (Jonsson, 1998; Scheuer and Keoleian, 2002). The specific environmental burdens considered by different rating systems may vary, but generally pertain to energy consumption, scarcity of raw materials, ecological damage caused by resource extraction, presence of harmful chemical compounds, and scale and types of waste streams (Jonsson, 1998). Examples of criteria include a 25% reduction in electricity compared to typical product operation, the use of 50% renewable primary resources in product manufacturing or the presence of less than 200 ppm of lead in the product. An overall rating is given to the product based on the number and types of criteria it meets. In general, a rating system does not *pass* or *fail* a product, but assigns ratings that reflect the degree of environmental performance (Jonsson, 1998).

A rating system that *does* pass or fail a product and then awards a certification based on a passing grade is typically referred to as an *eco-label* (Jonsson, 1998; Scheuer and Keoleian, 2002). Eco-labels are used to provide environmentally relevant information of a product to the consumer in order to stimulate market demand for environmentally benign products (Jonsson, 1998; Scheuer and Keoleian, 2002). Increased demand then encourages the adoption of more environmentally benign product manufacturing techniques and product functioning (Scheuer and Keoleian, 2002).

The level of detail presented within a product rating depends on the purpose of the rating system. In general, if a comprehensive environmental assessment of a product is the goal, a rating may present detailed information. If increased awareness towards the environmental performance of a product is the goal, then detailed information is not necessary (Brown, 2008; Scheuer and Keoleian, 2002). This latter point applies to eco-labels which *must* present simple and compact information that is easily understood by the general consumer (Jonsson, 1998; Scheuer and Keoleian, 2002). As a consequence, eco-labels do not typically describe to the consumer the methodologies by which the criteria are established and are criticized as providing "limited or no information describing the basis of the certification so consumers cannot evaluate the value of the label itself" (Scheuer and Keoleian, 2002). However, increased effort by government and third party organizations to improve the validity of eco-label certification processes has led to several well-established and transparent eco-labels (Scheuer and Keoleian, 2002).

There are various types of rating systems for both building operation and building products. The EnerGuide rating system grades household appliances and heating, ventilation and air conditioning (HVAC) systems based on energy consumption (OEE, 2007). The EnergyStar eco-label certifies household appliances and HVAC systems based on energy consumption (OEE, 2007). The R-2000 eco-label certifies an entire home based on space and water heating efficiency, potable water consumption and indoor air quality (OEE, 2007). The Forest Stewardship Council eco-label certifies wood products whose extraction and manufacturing are associated with reduced environmental burdens (Scheuer and Keoleian, 2002). In Europe, the Swan and the Eco-Label Award Scheme are but a few examples of eco-labels that certify various building products such as indoor paints, varnishes, insulation, flooring and building boards (Jonsson, 1998).

3.2 Rating Systems for Buildings

There are also rating systems for entire buildings. Criteria for such rating systems must address the broad range of environmental burdens attributable to buildings, as listed in Table B2 of Appendix B. A building, however, is often incapable of meeting all criteria (Jonsson, 1998; Scheuer and Keoleian, 2002). For example, a building constructed in a rural area cannot be placed in proximity to public transportation, while a building constructed in a high-density urban area cannot incorporate substantial green space. Rather than require the building adhere to *all* criteria, then, rating systems weight the various criteria by allocating a given number of points to each. A grade or certification is then assigned to a building based on an overall point score.

Though sound in theory, the development of a reasonable weighting system that fairly weighs the value of diverse criteria is difficult in practice. Indeed, criteria are often fundamentally incomparable (e.g. habitat preservation and indoor air quality). Thus, weighted assessment methods for buildings are criticized as oversimplifications which attempt to condense diverse criteria under a single measure (Scheuer and Keoleian, 2002). Further, ratings systems generally do not provide documentation of the methodologies used to weight criteria. Thus it can be difficult to meaningfully compare the environmental performance of two buildings which could conceivably achieve an equal rating or certification based on entirely different criteria (Scheuer and Keoleian, 2002).

An online database of rating systems developed worldwide for buildings has been compiled by the iiSBE (SBIS, 2008). Three rating systems within the database are currently usedd within Canada: Green Globes, SBTool, and LEED. Environmental performance categories and point allocations for each rating system are listed in Table C1 of Appendix C.

Green Globes is a rating system developed by BREEAM Canada (Building Research Establishment Environmental Assessment Method) and is used to "benchmark the energy and environmental performance of buildings, identify operational savings, increase tenant satisfaction and provide hands-on education for staff" (ECD, 2002). Green Globes may also award eco-label certification provided a third-party review of the certification process is conducted by an accredited architect or engineer (ECD, 2004). Green Globes has currently been applied to 19 case studies within Canada (ECD, 2008).

SBTool is a rating system developed by the iiSBE, an international non-profit organization with 36 member countries. SBTool is unique among rating systems in that the weighting of criteria is not constant, but can be varied to "reflect the varying importance of [environmental] issues in [each] region" (Larsson, 2007). The setting of weight parameters must, however, be done by a third party (Larsson, 2007). SBTool is not a commercially available rating system such as Green Globes, but acts rather as a generic framework for the development of other commercially available rating systems and eco-labels specific to a particular region (Larsson, 2007).

LEED is an eco-label developed by the USGBC, "a non-profit organization committed to expanding sustainable building practices" (USGBC, 2008). LEED is the only well-established eco-label for buildings in Canada and, indeed, the dominant eco-label for buildings worldwide (SBIS, 2008). There are 10,310 LEED-registered projects (not yet certified) and 1,327 LEED-certified projects in 65 countries (USGBC, 2008). Similar to Green Globes, LEED uses constant weighting between criteria.

3.3 Incorporating LCA into Rating Systems

LCA can be incorporated into rating systems for buildings to quantify environmental burdens associated with the manufacture of building products. Such burdens include the consumption of primary resources and the output of gaseous, liquid, and solid wastes. Eco-label criteria designed to reduce such burdens include the following:

- Use of reused materials
- Use of recycled materials
- Use of regionally extracted resources and regionally manufactured materials

Green Globes incorporates LCA into several of these criteria, as outlined in Table 3.1. LCI data for building materials are developed by the ASMI (GBI, 2008). However, documentation describing the methodology in which points are awarded based on LCI data is not publicly available.

SBTool also incorporates LCA into its criteria as outlined in Table 3.1. Points are awarded based on the embodied energy of building products and assemblies, quantified per unit floor area (iiSBE, 2007). LCI data used to calculate embodied energy are selected by the user (Larsson, 2007).

Table 3.1: Green Globes and SBTool LCA-based Environmental Performance Criteria

Rating System	Category	Objective	Criteria
Green Globes	Low Impact System and Materials	To select materials with the lowest life cycle environmental burdens and embodied energy	Select materials for structural, roof and envelope assemblies that reflect the results of a 'best run' LCA
	Minimal Consumption of Resources	To conserve resources and minimize the energy and environmental burdens of extracting and processing non-renewable materials	Specify materials from renewable sources that have been selected based on a LCA Specify locally manufactured materials that have been selected based on a LCA
SBTool	Non-renewable	To minimize the embodied	Meet threshold for embodied

	primary energy embodied in construction materials	primary energy used in the building	energy of structure, envelope and major interior assemblies, as determined by LCA

Sources: ECD, 2004; Larsson, 2007

Unlike the other two rating systems, LEED criteria do not incorporate LCA. Rather, the criteria for building products are based on percentage requirements established through pilot projects conducted in the late 1990s (Brown, 2008). Criteria pertaining to reused, recycled and regionally extracted and manufactured building products are summarized in Table 3.2.

Table 3.2: LEED Criteria pertaining to Building Products

Category	**Objective**	**Criteria**
MR3 – Reused materials	To reduce the “impacts resulting from extraction and processing of virgin materials”	5% (1 point) or 10% (2 points) of total value, by cost, of materials in the project are salvaged, refurbished, or reused.
MR4 – Recycled material	To reduce the “impacts resulting from extraction and processing of virgin materials.”	The sum of post-consumer recycled materials plus one-half of the pre-consumer recycled materials constitutes at least 10% (1 point) or 20% (2 points) of the total value, by cost, of the materials in the project.
MR5 – Regional materials	To support “the use of indigenous resources and reduc[e] the environmental impacts resulting from transportation.	10% (1 point) or 20% (2 points) of total value, by cost, of building materials are extracted, harvested, and manufactured within 800 kilometres of the building site.

Source: USGBC, 2005

3.4 Difficulties in Incorporating LCA into Rating Systems

LEED has not incorporated LCA into its criteria for two principal reasons: a lack of LCI data for all building products and the inherent subjectivity of LCA.

There are myriad different types of building products manufactured by myriad manufacturers in North America. Each building product is manufactured using a specific set of materials and technologies and has unique transportation requirements due to the locations of primary resources, the manufacturing facility and the building. LCI data are thus unique for each individual building product. To incorporate LCA into a rating system in a comprehensive manner would necessitate an LCI database containing data for *every* type of building product available in the market (Ayer, 2008). Such a database is not a present reality given the lack of LCI data for many building products. Current LCI databases, rather, are based on national averages for building products taken from one or a few data sources. Averaged data, however, are inaccurate to some degree and do not permit the comparison of similar products.

Moreover, LCI data depend to a large degree on the decisions and assumptions made by the LCA practitioner. A fair comparison of environmental performance of building products would require a standardized procedure for conducting an LCA that is applicable across the entire building industry (Ayer, 2008; Trusty and Horst, 2002). Such standardization currently does not exist.

3.5 The Ineffectiveness of Current LEED Criteria

There is growing interest in incorporating LCA into LEED reused, recycled and regional product criteria (Trusty, 2006). This interest is due to several deficiencies within the criteria, which prevent the criteria from promoting a measurable and consistent reduction of environmental burdens. Such deficiencies are described through Sections 3.5.1 to 3.5.4.

3.5.1 Cost-based Criteria

Cost-based criteria help streamline the data collection procedure since building product costs are generally well-documented while the masses, volumes or areas of building products are not (Heeger, 2008; Scheuer and Keoleian, 2002). Cost-based criteria weight expensive products more heavily than inexpensive products. However, high cost does not necessarily correlate to a high level of environmental burdens. For example, the purpose of reused and recycled product criteria is, in part, to reduce the quantity of disposed materials that are sent to landfills (USGBC, 2005). Mass or volume-based criteria, then, would correlate most closely to the reduction of environmental burdens in this case. Adherence to cost-based criteria, however, may result in high-cost but low-mass or volume products being diverted from the landfill. As a result, environmental burdens are not significantly reduced.

3.5.2 Rewarding the Status-Quo

A building may meet certain criteria though no effort was made to reduce environmental burdens. Consider a steel-frame building for example. Given the large quantity, high-cost, and high recycled content of structural steel (i.e. 90-95%), the building easily exceeds the recycled product criterion (Scheuer and Keoleian, 2002; Trust and Horst, 2002). Though recycled materials are indeed used, the purpose of LEED “is to stimulate change and move beyond status-quo practices” (Scheuer and Keoleian, 2002). In this example, the recycling criterion does not achieve this goal.

3.5.3 Non-Specific Resource Use

The recycled and reused product criteria make no differentiation between limited and bountiful resources or between environmentally burdensome and benign resource extraction techniques (Scheuer and Keoleian, 2002). To achieve the greatest reduction in environmental burdens, the criteria should target primary resources which either have limited availability or involve burdensome extraction techniques (Scheuer and Keoleian, 2002).

3.5.4 Universal and Inappropriate Criteria

Criteria are constant for all geographical regions. In some cases, varying the criteria to suit specific geographical conditions may be more appropriate. For example, the regional product criterion requires that products are manufactured and resources extracted within 800km of the building site. Adherence to this criterion is automatic in most major urban centres thus rewarding status-quo operation (Scheuer and Keoleian, 2002). The opposite is true in remote areas.

Further, thresholds may be too low for certain building scenarios thus rewarding status-quo operation, such as 10% recycled products in the case of a steel-frame building (Scheuer and Keoleian, 2002).

3.5.5 Incomplete Environmental Assessment

Criteria may promote the reduction of some environmental burdens, but an incomplete environmental assessment may fail to account for increased environmental burdens in other areas. The recycled product criterion, for example, does not account for the process energy of the recycling plant or the transportation of materials to and from the plant (Scheuer and Keoleian, 2002). For products that require significant process energy in recycling (e.g. plastics) or that are manufactured close to resource extraction sites but far from recycling facilities, adherence to the recycled product criterion may increase overall environmental burdens.

Finally, the adherence to current criteria typically requires the consideration of only a select number of building products. The remaining building products and their attributed environmental burdens are then effectively ignored.

3.6 Improving LEED Criteria using LCA

Provided comprehensive LCI databases are developed based on standardized data collection methodologies, then LCA becomes a powerful tool capable of improving and replacing the LEED reused, recycled and regional product criteria. The USGBC recognizes the deficiencies within LEED criteria and, as such, has initiated a research program to investigate the inclusion of LCA into LEED. A timeline for the program is not publicly available; however, deliverables of the program include the following:

1) A critical review of data sources to determine what products can be characterized with confidence by U.S-based data, what products need supplemental data from other sources, and what products lack reliable LCI data
2) A critical review of existing LCA tools and methods to determine how they may be used as a suitable basis for LEED credits
3) A standardized LCI data collection methodology applicable across the entire building sector to ensure a fair and consistent assessment of building products
4) Development of environmental burden-based criteria that are fairly weighted to other LEED criteria

(Trusty, 2006)

The first three deliverables address the present deficiencies within LCA, while the fourth deliverable addresses how LCA might ultimately be incorporated into the LEED rating system. There are several ways in which such incorporation may occur:

3.6.1 Modifications to Existing Percentage Requirements

The modification of percentage requirements within criteria will ensure a greater reduction of environmental burdens (Trusty, 2006). One option would be to vary percentage requirements for specific projects. A steel-frame building, for example, should adhere to a higher percentage requirement of recycled products than should a concrete or wood-framed building (Scheuer and

Keoleian, 2002). LCI data would help dictate the degree to which the percentage requirement should be increased.

Alternatively, criteria can be established for specific building products (e.g. 10% reuse of flooring products, 40% recycling of polyethylene vapour barrier, etc.). Percentage requirements for such criteria would be based on LCI data. Such criteria would target a specific set of environmental burdens since each building product is manufactured using specific materials and technologies. Though less compact than the existing criteria, the suggested criteria do not increase the time requirements of the certification process. The only difference between the current and proposed certification processes is the particular criterion to which each product is applied.

3.6.2 Replacing Cost-based with Physical Unit-based Criteria

The-cost based criteria should be replaced with physical unit-based criteria (mass, volume, area) (Scheuer and Keoleian, 2002). Such criteria would be developed using LCI data and would thus correlate well to the reduction of environmental burdens. To meet such criteria, architects and contractors would need to develop summaries of building products in physical units. However, such data are often already summarized in pre-tender estimates for a building. If not already summarized, data can usually be collected from design documents with a moderate increase in workload.

3.6.3 Selection of Specific Building Products from a Database

Criteria may be replaced by a list of building products that are pre-rated based on life cycle environmental performance (Trusty, 2006). Points would be awarded based on the selection of high ranked products and assemblies (Trusty, 2006). Such a scheme would simplify the rating system since the building designer would need only to choose appropriate products from a list rather than calculate the amount of recycled or reused content within individual building products. However, such a list would require the compilation of an LCI database containing environmental performance data for all building products available in the market. As discussed, such a database does not presently exist.

3.6.4 Environmental Burden-based Criteria

Product-based criteria may be replaced by environmental burden-based criteria that use LCI data to target specific environmental burdens (Trusty, 2006). For example, instead of requiring 10% recycled products to reduce environmental burdens in general, the criteria could be made more specific by requiring, for example, a 5% reduction in crude oil or a 20% reduction in CO_2e emissions compared to a status-quo scenario. Such criteria would not only explicitly address the limited availability of key resources and environmentally burdensome extraction techniques, but would also provide flexibility to architects and contractors in selecting which building products and assemblies to target.

Such an option, however, would require that an LCA be conducted for each building to be LEED-certified. This requirement increases both the complexity and time requirements of LEED certification, both of which are undesirable for a rating system. Such problems could be alleviated by designing an LCA software tool that incorporates an LCI database of all possible building products within the industry. Different arrangements of building products could then be chosen and the reduction of environmental burdens readily calculated. As discussed, however, such an LCI database does not presently exist.

3.7 Summary

The LEED eco-label for buildings has successfully increased market demand for building products with reduced environmental burdens. However, LEED environmental performance criteria pertaining to building products are not based on comprehensive environmental assessments and thus do not ensure a consistent reduction of environmental burdens. Provided its present deficiencies can be overcome, LCA will become an important tool in both the modification and redesign of LEED criteria for reused, recycled and regional building products.

4 GOAL, SCOPE AND LIFE CYCLE INVENTORY

In this chapter, the goal and scope of the study are established and LCI data for the Medical Sciences Building (MSB) product system are compiled. First, the purpose of the study and its intended audience are stated. System boundaries for the study are then established and data collection methodologies described for the selection of building products and the development of LCI data. Missing and inadequate data are identified and methodologies used to replace and modify such data are described. All LCI data for the building product system are provided in Appendices.

4.1 Goal

LCA can be incorporated into LEED reused, recycled and regional product criteria to promote a consistent reduction of environmental burdens. However, the lack of available LCI data and the absence of a standardized methodology for conducting an LCA are obstacles to the immediate incorporation of LCA into the criteria. The objective of this study is to use a case study to illustrate the benefits of and obstacles to LCA incorporation into LEED. The building selected as a case study is the MSB at the University of Victoria. MSB was constructed in 2004 and received Gold-level LEED certification.

The results of this study are intended for the following audience:

- Government and non-government organizations actively researching the incorporation of LCA into LEED. Specific organizations include the USGBC, Canadian Green Building Council (CaGBC), the ASMI, the iiSBE and BREEAM Canada.
- Other organizations or individuals interested in either the incorporation of LCA into LEED or the environmental performance of buildings in general. Organizations and individuals may include architects, contractors, governments, building managers and students.

Specific goals of the thesis include the following:

4.1.1 Assess the State of Public LCI Data

Critical to the incorporation of LCA into LEED is a regionalized public LCI database developed using standardized data collection methodologies. The current state of LCI data, in particular data availability and reporting transparency, is investigated by conducting an LCA on the case study building.

4.1.2 Compare LCI Methodologies

Standardized data collection requires that a specific LCI methodology is consistently used. The benefits and deficiencies of three LCI methodologies are explored and their results compared through the case study. LCI methodologies include PS-based, PMR-based and I/O-based LCI.

4.1.3 Assess Efficacy of Current LEED Criteria

Specific MSB building products are selected to meet the reused, recycled and regional product criteria. These selections result in a specific reduction of environmental burdens which is quantified using LCA. Product selection scenarios are then modeled that maximize and minimize the reduction of environmental burdens based on a constant total value of reused and recycled products. The extent to which environmental burdens are increased or decreased in these scenarios is quantified and discussed.

4.1.4 Explore Environmental Burden-based Criteria

The replacement of product-based criteria with environmental burden-based criteria ensures a measurable and consistent reduction of specific environmental burdens. The benefits of and difficulties in developing such criteria are discussed.

4.2 System Boundary

This section establishes the specific components to be modeled in this study, including building products and assemblies, life cycle stages, unit processes, flows and environmental burdens.

4.2.1 Building Products and Assemblies

This study considers the following building products and assemblies for analysis:

1) Structural assembly
    - Includes the foundation, columns and beams, walls and roof
    - Excludes decks, stairs and site infrastructure (e.g. paved walkways, patios, etc.)
2) Envelope assembly

  - Includes all insulation, weather and vapour barriers, roofing membranes, doors, windows and interior envelope products (e.g. gypsum wallboard and acoustic tile).
  - Excludes any PVC or aluminum trim (except on windows), hardware for doors (e.g. knobs, handles, etc.), cladding, sunshades and other exterior extensions

3) Interior finishing
  - Includes all types of flooring (e.g. carpet, linoleum, etc.) and paint.

4.2.2 Life Cycle Stages

LEED reused, recycled and regional product criteria apply only to building products initially installed in the building and not to replacement products installed over the building life cycle. Therefore, life cycle stages considered in this study include only those up to the delivery of products to the building, namely:

- Extraction of primary resources
- Manufacture of building products
- Reuse and recycling of building products, where applicable
- Intermediate transportation, including transport of all primary resources to manufacturing facilities, transport of products between manufacturing facilities and transport of final building products from manufacturing facilities to a distribution centre

4.2.3 Selection of Unit Processes and Flows

4.2.3.1 Process-based LCI

All data in this study are taken from existing literature. Thus, criteria for the inclusion of flows to and from a unit process (e.g. greater than 1% by mass) are pre-established and cannot be stipulated in this study. Criteria for the inclusion of unit processes, however, can be stipulated. Unit processes are continually added to the product system until all products are linked to resource inputs from the environment. For example, polyvinyl chloride (PVC) is a product input to the unit process for vinyl flooring manufacturing. According to the criteria, a unit process must be developed for PVC. Ethylene is a product input into PVC manufacturing. Thus a unit process must be developed for ethylene as well. This process is repeated until only environment inputs remain (crude oil, limestone, etc.).

ISO 14040 requires that the production of electricity and fuels be considered. The extent to which such production is accounted upstream must be established for PS-based LCI. Thus the following criteria (shown visually in Figure 4.1) are applied in this study:

- Electricity, fuel and transport inputs into product manufacture are accounted (Tier A inputs)
- Electricity and fuel inputs into Tier A transport inputs are accounted (Tier B inputs).
- Electricity, fuel and transport inputs into Tier A fuel inputs are accounted (Tier C inputs).
- Electricity and fuel inputs into Tier C transport inputs are accounted.
- Fuel inputs are accounted for all electricity inputs
- Primary energy resources are accounted for all fuel inputs.

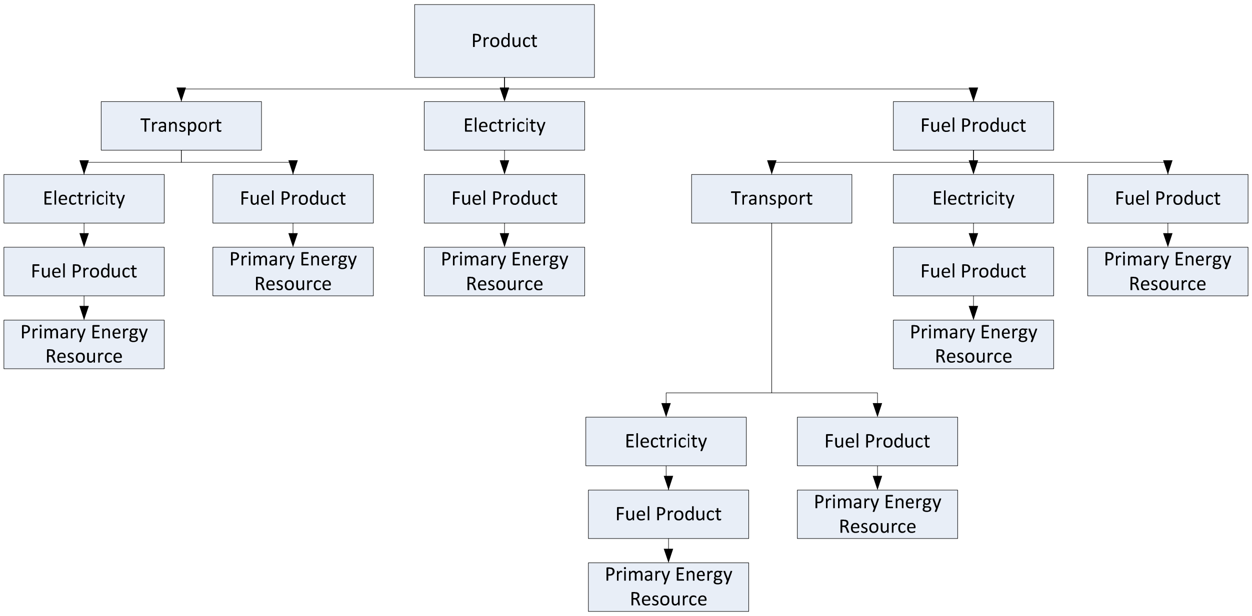

Figure 4.1: PS-based LCI System Boundary

4.2.3.2 I/O-based LCI

I/O tables for the Canadian economy are produced in three levels of industry aggregation as defined by the North American Industry Classification System (NAICS): S-level (26 industries), M-level (63 industries) and L-level (122 industries). L-level aggregation is selected for this study.

The selection of specific flows between industries is, of course, not possible with I/O-based LCI since I/O tables present only total aggregate monetary flows between industries. However, criteria are developed for the inclusion of industries such to equate, as best as possible, the system boundaries between I/O-based and process-based LCI. The criteria are as follows: Each resource and product flow identified within process-based LCI can be attributed to a particular industry in the I/O table. It is only these identified industries that are included in this study. All other industries are removed from the I/O table.

4.2.4 Environmental Burdens Considered

The following environmental burdens are considered in this analysis:

1) Carbon-dioxide equivalent (CO_2e) emissions by mass, calculated by multiplying the following greenhouse gases by their appropriate global warming factor:

$$CO_2e = CO_2 + \ 21 \times CH_4 + 310 \times N_20$$

2) Extraction of the following primary energy resources in units of energy:
    a. Crude oil
    b. Natural gas
    c. Coal
    d. Uranium oxide
    e. Hydropower

4.2.5 Functional Unit and Energy Content

The functional unit used in this study is 1 m^2 floor area. The energy content of all fuels in this study is expressed in higher heating value.

4.2.6 Data Quality Specifications

Data used in this study was chosen to be as applicable as possible to building construction in Victoria, British Columbia in 2004. Thus the following data quality criteria apply:

1) If a product is regionally manufactured (i.e. in British Columbia, Victoria, etc.), then LCI data for that region are used. Regional LCI data, however, are expected to be rare.
2) If regional data do not exist or are inadequate, then nationally averaged LCI data are used. Canadian-based data take priority over U.S-based data.

3) If nationally averaged data do not exist or are inadequate, then alternate data sources will be used, such as industrial end-use statistics for Canada or LCI data from another country.
4) Data should be as recent as possible. A 10-year limit before MSB construction (i.e. after 1994) is deemed sufficient for this analysis.
5) Data representing an average of available technologies will take priority in this study. Since all data are taken from other sources, it will be difficult to adhere to this requirement.

4.3 LCI Data Sources

4.3.1 Building Products

LCI data for building products are taken from two sources: the pre-tender estimate for the MSB (TBKG, 2003) and LEED Submission Document MRP1 – Materials and Resources Performance (MRP) (TBKG 2004). The pre-tender estimate provides building product and assembly quantities in various units of measurement (TBKG, 2003). Several assemblies listed in the pre-tender estimate do not specify product quantities (e.g. steel stud wall assembly, window assembly, etc.). In such cases, the AIE LCA software, developed by ASMI, is used to estimate product quantities within these assemblies.

The pre-tender estimate aggregates costs pertaining to products, equipment and labour in estimating the final cost of building products and assemblies. Such aggregated cost data are inadequate for this study. The MRP document, on the other hand, lists building product cost only. Further, these costs are actual and not estimated. MRP documents are thus used to develop cost data pertaining to MSB building products.

4.3.2 Process-based LCI

There are several process-based LCI data sources that meet the data quality parameters outlined in Section 4.2.6. This section provides a brief summary of each.

4.3.2.1 Athena Sustainable Materials Institute LCI Data

The ASMI provides several LCI reports for building products manufactured in Canada which together form the complete LCI data set used in the AIE software. The reports are meant to provide transparency in the research and data development process and must be purchased along with the software (ASMI, 2008). The reports are compiled by several different organizations contracted by ASMI. Several reports account for regional technologies and transportation requirements, while some are based on national averages. Most data are collected within Canada, though some data are referenced from international databases.

ASMI LCI reports will be the primary data source for building products provided the data are applicable to the MSB and the collection methodologies are sufficiently transparent.

4.3.2.2 NREL LCI Database

The National Renewable Energy Laboratory (NREL) has developed a public online LCI database for a range of products within the agricultural, construction, energy, metal, mineral, and transportation industries (NREL, 2005). Data are collected within the U.S. and are based primarily on national averages with occasional regionalization. Data are compiled by several different organizations contracted by NREL.

The NREL LCI database will be the primary data source for energy resources and products (coal, gasoline, electricity, etc.) and the secondary data source for building products.

4.3.2.3 BEES LCI Database

Building for Environmental and Economic Sustainability (BEES) LCI database is developed by the National Institute for Standards and Technology (NIST) (Lippiatt, 2007). Data are collected within the U.S. and are based on national averages. Data are either collected directly by contracted firms or are referenced from the NREL LCI database.

The BEES LCI database will be the tertiary source for building product manufacture data.

4.3.2.4 Statistics Canada Metal and Non-metal Mining Data

Statistics Canada (StatsCan) publishes annual reports on metal and non-metal mining industries in Canada (StatsCan 2007a, StatsCan 2007b). Included within these reports are data pertaining to the annual quantities of extracted minerals and fuel consumed. Data are not based on LCA but on surveys.

Thus, reported fuel consumption may include heating and electricity loads for administrative facilities, lodging, etc. However, reported fuel consumption is predominately attributable to resource extraction processes (Nyboer, 2008). Thus, the survey data are reasonably accurate substitutes when LCI data are not available.

4.3.2.5 Environment Canada CO_2e Emission Data

CO_2e emissions pertaining to fuel combustion are based on emission factors listed in Environment Canada's *National Inventory Report, 1990-2005: Greenhouse Gas Sources and Sinks in Canada* (ECGGS) (Environment Canada, 2007). A summary of emission factors for various fuels and processes modeled in this study is presented in Table D1 of Appendix D.

4.3.2.6 Additional Data Sources

LCI data from the Swedish Centre for Environmental Assessment of Product and Material Systems (CPM) database is used for LCI data that are either unavailable or inadequate in the previously described sources (CPM, 2008).

4.3.3 I/O Based LCI

There are several I/O-based LCI data sources that meet the data quality parameters outlined in Section 4.2.6. This section provides a brief summary of each.

4.3.3.1 National Symmetric Input-Output Tables

The I/O table used for this study is the 2004 *National Symmetric Input-Output Table for Canada*, at L-level aggregation and in modified basic price structure (StatsCan, 2008a). Modified basic price is defined as the "amount receivable by the producer from the purchaser for a unit of a good or service produced as output minus any tax payable…[excluding] any transport charges invoiced separately by the producer" (Lal, 1999). Building product cost data used in this study do not include taxes or transport charges. Thus, the selected I/O table is suitable for this analysis.

4.3.3.2 CIEEDAC

The Canadian Industrial Energy End-Use Data Analysis Centre (CIEEDAC) is a research centre within the School of Resource and Environmental Management at Simon Fraser University. CIEEDAC is contracted by Statistics Canada and Natural Resources Canada to compile fuel consumption statistics for Canadian industries based on surveys. A database of fuel consumption and CO_2e emissions for industries in Canada, at various levels of NAICS industry aggregation, is publicly available online (CIEEDAC, 2004).

CIEEDAC is the primary source for fuel consumption data for all industries considered in this study.

4.3.3.3 Statistics Canada Transportation Publications

CIEEDAC does not include fuel consumption data for transportation industries. Rather, such data are obtained from several StatsCan annual reports on transportation industries, including the following:

- Trucking in Canada – Catalogue # 53-222-XIE (StatsCan, 2005a; StatsCan, 2006a)
- Rail in Canada – Catalogue # 52-216-X (StatsCan, 2005b; StatsCan, 2006b)
- Shipping in Canada – Catalogue # 54-205-X (StatsCan, 2000; StatsCan, 2006c)
- Natural Gas Transportation and Distribution – Catalogue # 57-205-XIB (StatsCan, 2003)
- Operating Statistics of Canadian Pipelines, monthly – CANSIM Table 133-0002 (StatsCan, 2008b)
- Operating Statistics of Canadian Natural Gas Carriers, monthly – CANSIM Table 129-0001 (StatsCan, 2008c)

4.3.3.4 Environment Canada CO_2e Emission Data

Similar to process-based LCI, CO_2e emissions pertaining to fuel combustion are based on Environment Canada's ECGGS report (Environment Canada, 2007).

4.4 Data Collection Methodologies and Summaries

In this section, the methodologies by which data are collected for building products, process-based LCI and I/O-based LCI are described. General problems with the data are summarized while more detailed explanations and final LCI data are presented in Appendices.

4.4.1 Building Product and Assembly Summary

Detailed descriptions of various building products and assemblies are taken from the pre-tender estimate are listed in Table E1 of Appendix E. Also included in Appendix E are any assumptions and estimations made in developing the data. Unit conversion factors (e.g. m^3 to kg) for building products and assemblies are listed in Table E2 of Appendix E. The AIE is used to quantify building products within the following assemblies:

- Steel stud wall
- Curtain wall and window assemblies

Final building product quantities used for process-based LCI are summarized in Table 4.1.

Table 4.1: MSB Building Product Quantity Summary

Aluminum (kg)	10,269
Asphalt (kg)	1,195
Ceramic tile (m^2)	467.0
Clay brick (kg)	192,567
Concrete - 30 MPa (m^3)	1,956
Ethylene-propylene-diene monomer rubber (kg)	312.7
Fiberglass insulation (kg)	907.4
Gypsum wallboard - 16mm (m^2)	10,852
Latex paint (kg)	25,850
Linoleum flooring (m^2)	2,053
Nylon carpet (m^2)	465.0
Plywood (kg)	5,879
Polyethylene vapour barrier - 6 mil (kg)	540.8
Polypropylene fabric (kg)	706.2
Polystyrene insulation (kg)	6,137
Sand and gravel (kg)	986,464
Steel - Galvanized Sheet (kg)	6,998
Steel - Galvanized Studs (kg)	45.34
Steel nails (kg)	101.6
Steel rebar (kg)	299,909
Steel - Screws, nuts, and bolts (kg)	1,292
Styrene-butadiene-styrene roofing membrane (kg)	6,472
Vinyl flooring (m^2)	63.00
Window (m^2)	787.4

Specific building product costs taken from the MRP and correlated to the appropriate L-level industry are listed in Table E3 of Appendix E. Table 4.2 expresses the value of all building products used in the MSB in terms of L-level industries.

Table 4.2: MSB Building Product Values Correlated to L-level Industry Output

Industry	**Output ($)**
Non-metal mineral product manufacturing[1]	765,870
Fabricated Metal Manufacturing	455,138
Miscellaneous Chemical Product manufacturing	48,080
Plastic Product Manufacturing	146,867
Textile and Textile Product Mills	31,500
Petroleum and Coal Product Manufacturing	28,330
Wood Product Manufacturing	22,028
Non-metallic mineral mining	70,000
Total:	**1,567,813**

[1] - two L-level industries, Cement and Concrete Product Manufacturing and Miscellaneous non-metal Mineral Product Manufacturing, are aggregated in this case. Reasons for such aggregation are given in Section 4.4.3

4.4.2 Process-based LCI

A total of 78 unit processes are developed for process-based LCI such that each product considered in this analysis is linked to primary resource inputs from the environment. Inputs and CO_2e emissions specific to each unit process are listed in Appendix F.

Unavailable or inadequate LCI data were frequently identified. As such, various assumptions, estimations and alternate data selections were made. Appendix G describes the methodologies used to address unavailable or inadequate LCI data for each unit process. The following provides a summary of the general LCI data deficiencies.

4.4.2.1 ASMI LCI Data Transparency

ASMI LCI reports are compiled by various contracted organizations. Data collection and reporting guidelines developed by ASMI are designed to provide consistency and transparency in reporting and collection procedures (ASMI, 1997). In particular, the guidelines specify that “three main stages of production will be recognized and kept separate in analysis – extraction/benefaction of raw materials, primary processing and secondary processing” (ASMI, 1997). Based on these requirements, one would expect both the flows for each unit process as well as the total flows between the environment and the product system to be adequately documented.

Several ASMI LCI reports considered for this study, however, present only total flows between the environment and the product system (crude oil, limestone, etc.) but not intermediate products (gasoline, lime, etc.) (Franklin Associates, 2001; MES, 2003; Norris, 1999). Inherent in the compilation of such flows are key decisions made by the practitioner: First, the practitioner must develop or use existing data for such unit processes as resource extraction, petroleum refining, electricity generation and other manufacturing processes. Second, the practitioner must use a specific LCI methodology to account for upstream processes and flows for each unit process. However, the development of these unit processes and selection of LCI methodology are neither described nor referenced in these reports. Further, data presentation is unclear in two of these reports (Franklin Associates, 2001; Norris, 1999). For example, multiple listings of 'gas' are presented in various units with no clear indication of what exactly is quantified (Franklin and Associates, 2001; Norris, 1999).

Thus, the data in these reports are difficult to interpret and are inadequate for use in this study.

4.4.2.2 Transport Data Omissions

StatsCan annual reports on truck and rail transport industries are used to develop alternate LCI data where missing or inadequate transport data from other sources are identified. First, two ASMI reports (Franklin and Associates, 2001; Norris, 1999) fail to explicitly indicate whether transport is even considered in the analysis. Next, the NREL LCI database only lists transport of the final product to a distribution centre or consumer for energy resources and products but not other products (NREL, 2005). Finally, BEES LCI data either do not account for transportation or do not justify the estimations made (Lippiatt, 2007). The following describes the alternate LCI data development methodology:

1) All transport is assumed to occur within Canada. Transport modes considered are truck and rail. Freighter and barge transport of products within Canada are assumed to be negligible. Data sources used are *Trucking in Canada – 2003* and *Rail in Canada – 2003* (StatsCan, 2005a; StatsCan, 2005b). More recent publications are available but do not provide sufficiently disaggregated transport data for products.

2) *Trucking in Canada – 2003* lists total tonne-kilometres and total tonnage transported within Canada for aggregate product groups. The ratio of the two gives the average kilometre distance traveled for each aggregate product group. By multiplying this distance by the mass of a product, the tonne-km transport requirement is estimated. Truck transport requirements per kg of product are listed in Table H1 of Appendix H.
3) *Rail in Canada – 2003* lists both the average distance traveled by all products and the tonnage of aggregate product groups transported between provinces. Two methods are used to develop rail transport requirements in tonne-km units:
    a) For building products transported from the manufacturing facility to the distribution centre, aggregate product group transport data to BC is used. Distances between provinces are estimated based on distances between capital cities (NRCan, 2006). A weighted average travel distance for each product group is calculated based on relative tonnage transported from each province. This distance is multiplied by the mass of a specific building product to estimate the transport requirement in tonne-km.
    b) For intermediate products and resources whose origins and destinations are unknown, the average distance traveled by rail for all products is assumed (743 km).

    Rail transport requirements per kg of product are listed in Table H2 of Appendix H.
4) Due to product aggregation in the StatsCan reports, it is impossible to determine whether a specific product is transported only by truck, only by rail, or by both. To avoid double counting, it is assumed that a product is transported *either* by truck or rail but never both. Transport requirements are weighted by relative tonnage transported. For example, if 2,000 kilotonnes of non-metallic mineral products are transported an average of 800km by rail and 500 kilotonnes are transported an average of 70km by truck, then the average transport distances per trip are:

    a. Rail: $\frac{2000}{2000+500} \times 800km = 640$ km
    b. Truck: $\frac{500}{2000+500} \times 70km = 14$ km

    The average distance is then multiplied by the mass of the product to estimate transport requirements in tonne-km.

If, however, a product appears more disaggregated in one transport mode than the other (e.g. window assembly listed as 'glass and glass products' for truck and 'non-metallic mineral products' for rail) then *all* transport is allocated to the more disaggregated listing.

A summary of transport requirements for products based on the methodology just described is listed in Table H3 of Appendix H.

4.4.2.3 Resource Extraction

Two ASMI LCI reports assume 0.027 GJ of diesel are consumed per tonne of *all* non-energy primary resources extracted (Venta, 1997; Venta, 1998). No justification, however, is given for such a value. Thus, this value is not adopted in this study. In its place, fuel consumption data provided by StatsCan annual reports on metal and non-metal mining industries are used (StatsCan 2007a; StatsCan 2007b).

4.4.2.4 CO_2e Emissions

CO_2e emissions related to fuel combustion are generally not reported in the LCI data. Thus, ECGGS emission factors are easily applied in most cases. In a few cases, however, CO_2e emission data for fuel combustion are embedded in the LCI data and cannot be distinguished between non-combustion CO_2e emissions (e.g. calcination). In such cases, LCI data for CO_2e emissions are used in place of ECGGS data.

4.4.3 I/O-Based LCI

Based on the industry selection criteria established in Section 4.2.2, 25 industries are included in the I/O table for this study. The I/O table is listed in Appendix I. Fuel consumption factors are based principally on CIEEDAC data. All combustion-based CO_2e emission factors are taken from ECGGS; non-combustion emission factors are taken from CIEEDAC data.

Unavailable or inadequate LCI data were frequently identified within the CIEEDAC database, including the following:

- Several fuels are often listed as inputs into an industry but are not quantified. Rather, a 'confidential' cumulative total of these fuel inputs is listed. Where this occurs, the cumulative total is allocated equally among the fuel inputs of unknown quantity.
- There is missing data for the Cement and Concrete Product Manufacturing industry (NAICS 3273) as CIEEDAC lists data for cement but not concrete. Thus the industry is merged with

Miscellaneous Non-Metallic Mineral Product Manufacturing (NAICS 327A) within the I/O table to form the aggregate industry Non-Metallic Mineral Product Manufacturing (NAICS 327). CIEEDAC has fuel consumption data for this aggregate industry.

- Inputs of steam energy are omitted due to the uncertainty in how steam was produced.
- ‘Middle distillates’ are assumed to be diesel.

Moreover, CIEEDAC does not provide data for several L-level industries. The data development methodologies used in these cases are as follows:

4.4.3.1 Truck Transport

Truck transportation data are taken from StatsCan annual *Trucking in Canada* reports for the years 2003 and 2004 (StatsCan, 2005a; StatsCan, 2006a). Data reporting is at L-level NAICS industry aggregation and is thus consistent with this study. 2004 data lists only the total tonnage of products transported. 2003 data, however, also lists average transport distance. This average transport distance is assumed for 2004 as well. Total tonne-km transported are calculated by multiplying total tonnage by average transport distance. NREL LCI data are then used to calculate total fuel consumption, which is divided by the total output from the industry to calculate the fuel consumption factor per unit industry output (NREL, 2005). Summary calculations are listed in Appendix J.

4.4.3.2 Rail Transport

Rail transportation data are taken from the StatsCan annual report *Rail in Canada* for the year 2004 (StatsCan, 2006b). Data reporting is at L-level NAICS industry aggregation and is thus consistent with this study. Total fuel consumption by the industry is listed in the report. This total is divided by the total output from the industry to calculate the fuel consumption factor per unit industry output. Summary calculations are listed in Appendix J.

4.4.3.3 Water Transport

Water transportation data are taken from the StatsCan annual reports *Shipping in Canada* for the years 1998 and 2004 (StatsCan, 2000; StatsCan, 2006c). Data reporting is at L-level NAICS industry aggregation and is thus consistent with this study. Only 1998 data list fuel consumption by the industry. An estimate of fuel consumption for 2004 is calculated based on the ratio of total tonnage transported between 2004 and 1998. NREL LCI data are used to convert mass into volume units (NREL, 2005). This total is divided by the total output from the industry to calculate the fuel consumption factor per unit industry output. Summary calculations are listed in Appendix J.

4.4.3.4 Pipeline Transport

Pipeline transport includes the transport of crude oil, petroleum products, natural gas and coal slurry. Data for coal slurry transport could not be found and is omitted from analysis. Transport data for crude oil and petroleum products are taken from Canadian Socioeconomic Information Management (CANSIM) *Table 133-0002 – Operating Statistics of Canadian Pipelines, monthly* (StatsCan, 2008b). Total m^3-km transported is converted to tonne-km based on the density for crude oil listed in the NREL LCI database (NREL, 2005). NREL LCI data are also used to related total tonne-km transported into total electricity consumption (NREL, 2005). Total electricity consumption is divided by the total output from the industry to calculate the electricity consumption factor per unit industry output.

Transport of natural gas is separated into two NAICS L-level industries:

- Pipeline transport (NAICS 4860)
- Natural Gas Distribution, Water, Sewage and other systems (NAICS 221A)

NAICS 4860 incorporates natural gas transport from extraction fields to the distribution centre. NAICS 221A incorporates natural gas transport from a distribution facility to the final consumer. Data from *CANSIM 129-0001 – Operating Statistics of Canadian natural gas carriers, monthly* list total tonne-km of natural gas transported in 2004 (StatsCan, 2008c). Data, however, could not be found that separates this total into the two industries. Therefore, total tonne-km transport requirements are divided based on the relative lengths of pipeline and distribution systems as listed in StatsCan Annual Report *Natural Gas Transport and Distribution* (StatsCan, 2003). Total tonne-km transported are converted into total natural gas consumption based on NREL LCI data (NREL, 2005). Total natural gas consumption is divided by the total output from the industry to calculate the natural gas consumption factor per unit industry output.

4.4.3.5 Forestry and Logging

NREL LCI data for the production of plywood in the Pacific Northwest are used to develop fuel consumption factors per unit volume of wood harvested (NREL, 2005). Considered life cycle stages are harvesting of wood and replanting of forests with seedlings. Total amount of wood harvested within Canada in 2004 is taken from the National Forestry Database Program (NFDP, 2007). Total fuel consumed by the forest industry in 2004 is calculated by multiplying total wood harvested by the fuel consumption factors. Total fuel consumed is then divided by the total output from the industry to calculate the fuel consumption factor per unit industry output. Summary calculations are listed in Appendix J.

4.4.3.6 Oil and Gas Extraction

NREL LCI data for crude oil and natural gas extraction are used to develop fuel consumption factors data per volume extracted. Total production of crude oil and natural gas in 2004 is taken from the Energy Statistics Handbook (StatsCan, 2007c). Total fuel consumed is calculated by multiplying total production by fuel consumption factors. Total fuel consumed is then divided by the total output from the industry to calculate the fuel consumption factor per unit industry output. Summary calculations are listed in Appendix J.

4.4.3.7 Coal Mining

NREL LCI data for coal mining are used to develop fuel consumption factors data per mass of coal mined. Total production of coal in 2004 is taken from the StatsCan publication Energy Statistics Handbook (StatsCan, 2007c). Total fuel consumed is calculated by multiplying total production by fuel consumption factors. Total fuel consumed is then divided by the total output from the industry to calculate the fuel consumption factor per unit industry output. Summary calculations are listed in Appendix J.

4.5 Summary

The goals of this study are to assess the state of public LCI data, compare LCI methodologies, assess the efficacy of LEED criteria and explore alternative environmental burden-based criteria. To meet these goals, an LCA is conducted on the LEED-certified MSB at the University of Victoria. In this Chapter, the system boundary, data collection methodologies and LCI data sources for this LCA study are established.

In addition, total quantities and costs of building products are listed. Data gaps and inadequacies are frequently identified in the compilation of LCI data. In such cases, alternate data are developed based principally on StatsCan publications.

5 LCI RESULTS

In this chapter, primary energy (PE) consumption and CO_2e emissions (herein referred together in this Chapter as environmental burdens) for the Medical Sciences Building (MSB) are presented for each of the three LCI methodologies. Inventory development and the quality of LCI results for each methodology are discussed and compared. PMR-based LCI methodology and results are selected for further use in this study. They are used to calculate environmental burdens per unit floor area and the ratio of embodied to operational environmental burdens. These calculations are compared to those from other LCA studies. Finally, PMR-based LCI data are used to allocate environmental burdens to individual products and assemblies in the MSB.

5.1 LCI Results Discussion and Comparison

Table 5.1 presents the results from each LCI methodology both in absolute value and relative to PMR-based results. Figure 5.1 illustrates only PE consumption and CO_2e emissions estimated using each methodology. Table K1 in Appendix K lists total output for all products for each LCI methodology.

Table 5.1: Environmental Burden Estimations for all LCI Methodologies

	PMR-Based Total	**PS-Based**		**I/O-Based**	
		Total	**Compared to PMR**	**Total**	**Compared to PMR**
Primary Energy Consumption (GJ)	**18,201**	**17,475**	**-4.0%**	**22,903**	**+20.5%**
Natural Gas	6,925	6,601	-4.7%	8,454	+18.1%
Crude Oil	3,900	3,693	-5.3%	5,421	+28.1%
Bituminous Coal	2,602	2,592	-0.4%	2,436	-6.4%
Uranium Oxide	1,842	1,772	-3.8%	2,465	+25.3%
Hydropower	1,839	1,769	-3.8%	2,462	+25.3%
Sub-bituminous Coal	806	775	-3.8%	1,223	+34.1%
Lignite Coal	287	276	-3.8%	442	+35.1%
CO_2e Emissions (tonnes)	**1,297**	**1,279**	**-1.4%**	**2,431**	**+46.6%**

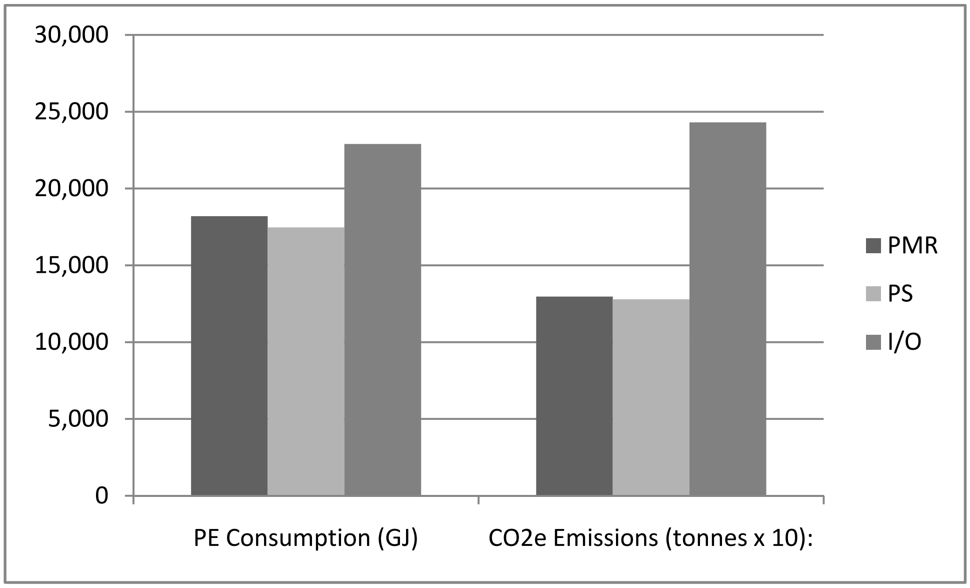

Figure 5.1: Environmental Burden Estimations for each LCI Methodology

5.1.1 PMR-Based LCI

Environmental burdens of 4.45 GJ PE/m^2 and 317 kg CO_2e/m^2 are calculated. These results are considered the most accurate of the three LCI methodologies due to the complete accounting of upstream processes. Moreover, the compilation of all data into a single matrix allows for an organized and systematic analysis. Unit processes or flows were added to, removed from or modified within the product system with ease. Further, the ability to use matrix inversion techniques to easily compute results was particularly beneficial given the amount of data considered in this study.

5.1.2 PS-Based LCI

Environmental burdens of 4.28 GJ PE/m^2 and 313 kg CO_2e/m^2 are calculated, 4.0% and 1.4% less than PMR-based results, respectively. A computer model was developed to calculate and cumulate flows for all 78 unit processes in this study in accordance with the PS-based LCI system boundary established in Section 4.2.2. The development of such a model resulted in increased time requirements for analysis relative to PMR-based LCI. Further, the incomplete accounting of upstream processes led to underestimated environmental burdens. Accuracy could be improved by including additional upstream unit processes within the system boundary or by using convergence formulas to solve for total upstream flows (Suh and Huppes, 2005). Both techniques, however, further increase the time requirements of the LCI and are not explored in this study.

5.2.3 I/O-Based LCI

Environmental burdens of 5.61 GJ PE/m^2 and 595 kg CO_2e/m^2 are calculated, 20.5% and 46.6% more than PMR-based results, respectively. This large increase in results was anticipated. I/O-based LCI accounts for *all* PE consumption and CO_2e emissions attributed to an industry, including those pertaining to the heating and lighting of administrative facilities, the operation of cleaning and maintenance equipment, the storage of products, etc. Process-based LCI, on the other hand, accounts for only certain processes within an industry that directly contribute to the manufacture of a specific product. Since I/O-based LCI accounts for more activities than process-based LCI, its calculations of environmental burdens are generally higher.

However, these higher results may simply be erroneous. In this study, environmental burdens were aggregated across a diverse range of products within an industry creating large uncertainty in results. Uncertainty is particularly evident in the non-metal mineral product manufacturing industry (NAICS 327) which outputs 48.8% of building products in this study. NAICS 327 products are diverse and include many products not used in the MSB. Thus, the weighted environmental burdens per unit output of the industry are unlikely to reflect those of MSB building products. A comprehensive assessment of uncertainty in I/O-based results due to industry aggregation is beyond the scope of this study.

Uncertainty in results is further compounded by confidential fuel inputs within 10 of the 24 industries modeled in this study. In particular, confidential inputs of coal, coal coke, steam and wood waste into NAICS 327 constitute 29.6% of total fuel input to an industry that outputs 48.8% of MSB building products. The methodology developed in this study partitions confidential fuel equally among the unknown fuel inputs (i.e. 25% coal, 25% coal coke, etc.). If, however, all confidential fuel input into NAICS 327 is assumed to be bituminous coal, then overall LCI results for the MSB change significantly, as shown in Table 5.2. This one fuel input modification to one industry results in an overall addition of 78.7% bituminous coal and 8.4% PE consumption in the MSB. A detailed analysis of uncertainty in LCI results due to all confidential fuel inputs is beyond the scope of this study.

Table 5.2: Confidential Fuel Partitioning within NAICS 327 and the Impact on LCI Results

	Life Cycle Inputs for MSB		**Percentage Change**
	Equal Partitioning of Confidential Fuel	**100% Bituminous Coal**	
Bituminous Coal (GJ)	2,436	4,353	+78.7%
Total Primary Energy (GJ)	22,903	24,821	+8.4%
CO_2e Emissions (tonnes)	2,431	2,488	+2.3%

5.2.4 Selection of Most Qualified Methodology

PS-based LCI requires increased time to compute results and underestimates environmental burdens due to an incomplete modeling of upstream processes. I/O-based LCI computes results with high uncertainty. PMR-based LCI, on the other hand, computes results within a complete, convenient and consistent mathematical framework. PMR-based LCI is thus the most qualified LCI methodology and is used exclusively for the remainder of this study.

5.3 Comparison to Other Studies

5.3.1 Floor Area Metrics

PE consumption per unit floor area of the MSB is the lowest of those found in other LCA studies of concrete buildings, by a small margin. Comparisons are shown in Figure 5.2. This result is due in part to the specific system boundary selected for this study. Only the structural and envelope assemblies and envelope-related interior finishings (e.g. flooring and paint) are modeled in this study. Several other studies include additional products and assemblies such as household appliances, other interior finishing products (e.g. counters, PVC trim, door hardware, etc.) and site infrastructure (e.g. walkways, stairs, etc.). Further, this study did not consider the building product replacement phase of the MSB in overall PE consumption, whereas some of the other studies did.

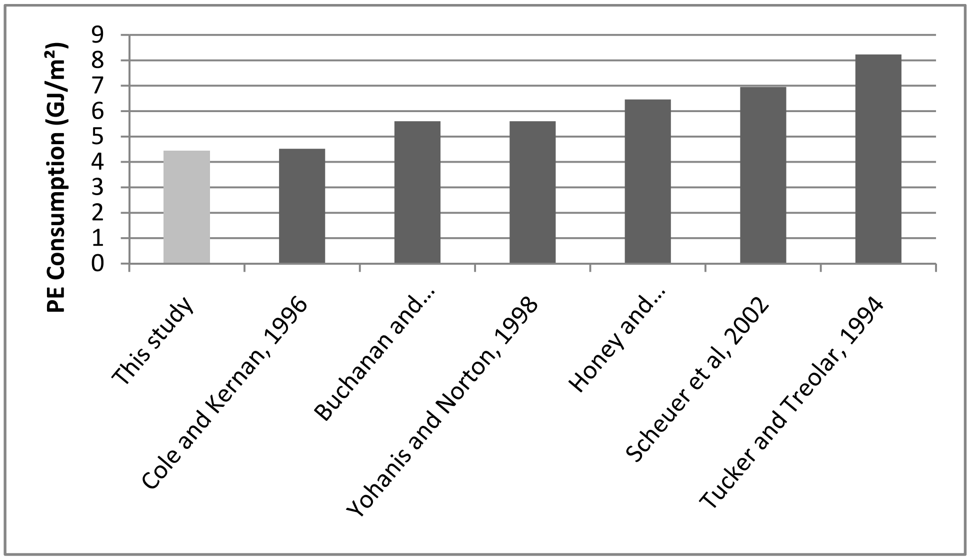

Figure 5.2: PE Consumption Comparison with other LCA Studies on Concrete Buildings

CO_2e emissions pertaining to the MSB are comparable to those found in other LCA studies. Comparisons are shown in Figure 5.3. Again, the system boundaries particular to each study will impact results. In addition, the types of fuel input into building product manufacturing will also impact results. For example, electricity inputs in this study have relatively low CO_2e emission intensity due to the average generation mix in Canada (i.e. 57% hydropower, 17% coal, 16% nuclear, 5% natural gas, 4% other). If the average fuel inputs into U.S. electricity generation (NREL, 2005) were modeled instead, CO_2e emissions for the MSB increase from 317 to 426 kg CO_2e /m^2, or 34%.

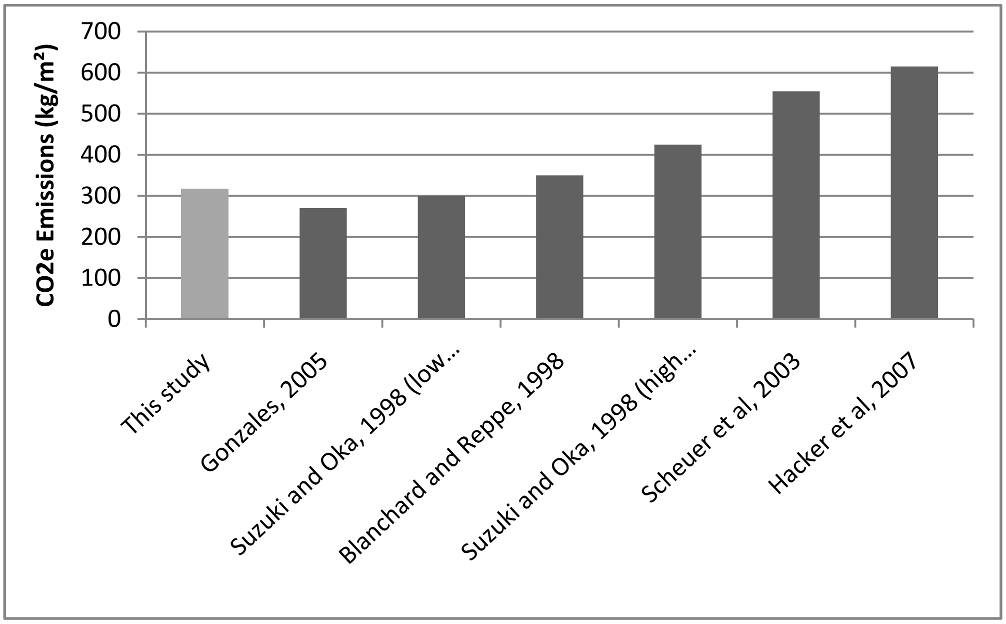

Figure 5.3: Embodied CO_2e Emissions Comparison with other LCA Studies on Concrete Buildings

5.3.2 Embodied to Annual Operational Ratio

Estimated operational energy (i.e. electricity and natural gas) for the MSB is based on the Energy and Atmosphere section of the LEED submission document (HWT, 2004). Total PE consumed in the production of electricity and natural gas is considered in addition to the direct energy requirements of the MSB. For comparison purposes, operational electricity is assumed to be produced by the average Canadian electric grid and not the British Columbia electric grid (i.e. 93.8% hydro, 4.7% natural gas, 1.5% other) The inclusion of PE consumption increases overall operational energy from 6,363 GJ to 9,801 GJ (54%) and operational CO_2e emissions from 207 tonnes to 250 tonnes (21%). The large increase in the former is attributed to the low conversion efficiencies of primary energy resources into electricity.

Ratios of embodied to annual operational environmental burdens are listed in Table 5.3. The CO_2e emission ratio is nearly three times larger than the PE consumption ratio. This difference is attributed to the difference in CO_2e emission intensity of embodied and annual operational energy. Significant quantities of fuels with high CO_2e emission intensity (i.e. coal, gasoline, diesel, residual fuel oil) contribute to embodied energy. Apart from electricity generation, none of these fuels contribute to operational energy. Rather, natural gas is the predominate fuel, which has a comparatively lower CO_2e emission intensity than other fossil fuels.

Table 5.3: MSB Embodied to Annual Operational Environmental Burden Ratios

	PE Consumption	**CO_2e Emissions**
Embodied	18,201 GJ	1,297 tonnes
Annual Operational	9,801 GJ	250 tonnes
Ratio	1.86	5.20

The embodied to annual operational PE consumption ratio for the MSB is low compared to other LCA studies, as shown in Figure 5.4. Again, the system boundaries particular to each study will impact this ratio. In addition, increased operational energy will reduce the ratio. Since the MSB is an educational facility equipped with medical and computer laboratories, its operational energy is higher than that of a residential or office building, which are modeled in all but one of the other LCA studies. Further, some buildings modeled in the other LCA studies incorporate significant quantities of reused and recycled products and are designed to require minimal operational energy. Both of these factors increase PE consumption ratios. Finally, the consideration of primary rather than direct operational energy decreases the ratio for the MSB. It was not made clear in most other studies whether primary or direct operational energy was considered.

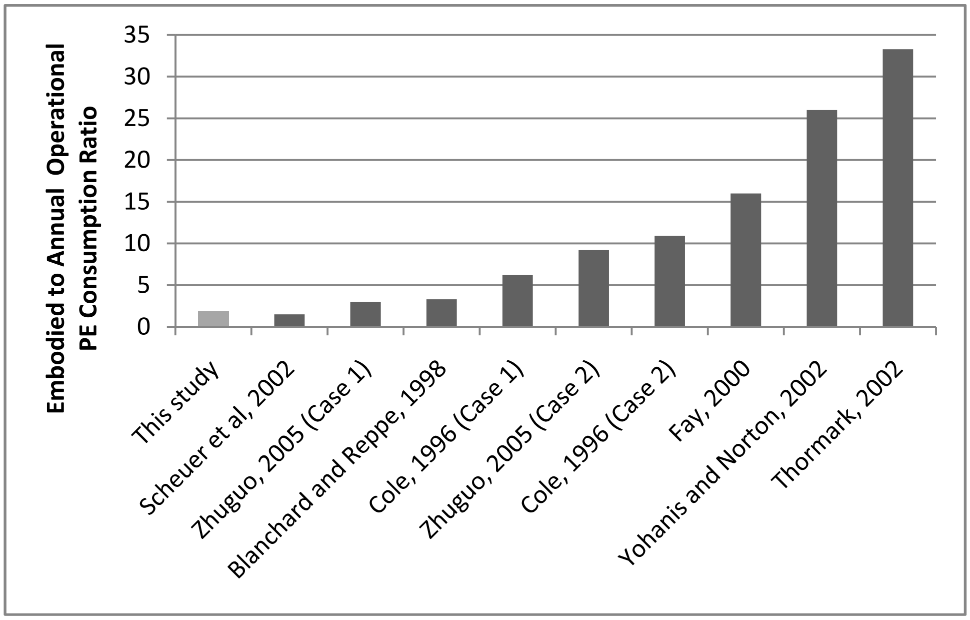

Figure 5.4: Comparison of Embodied to Annual Operational PE Consumption Ratio

The embodied to annual operational CO_2e emissions ratio for the MSB is comparable to that of other LCA studies, as shown in Figure 5.5. Each of the factors that impact the PE consumption ratio also impact the CO_2e emissions ratio.

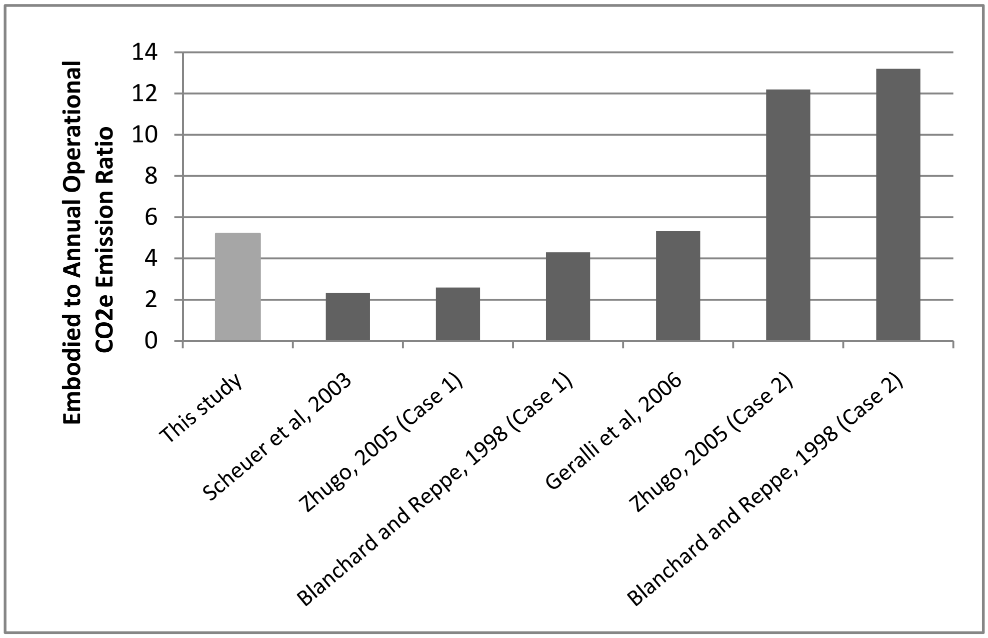

Figure 5.5: Comparison of Embodied to Annual Operational CO_2e Emissions Ratio

5.4 Primary Energy and CO_2e Emissions Allocation to Products

Each building product in the MSB accounts for a percentage of overall environmental burdens. These percentages are illustrated in Figure 5.6. The majority of environmental burdens are attributed to the concrete and steel rebar in the structural assembly. In particular, concrete accounts for nearly half of all CO_2e emissions, largely due to the calcination of limestone in concrete production (24% of total CO_2e emissions).

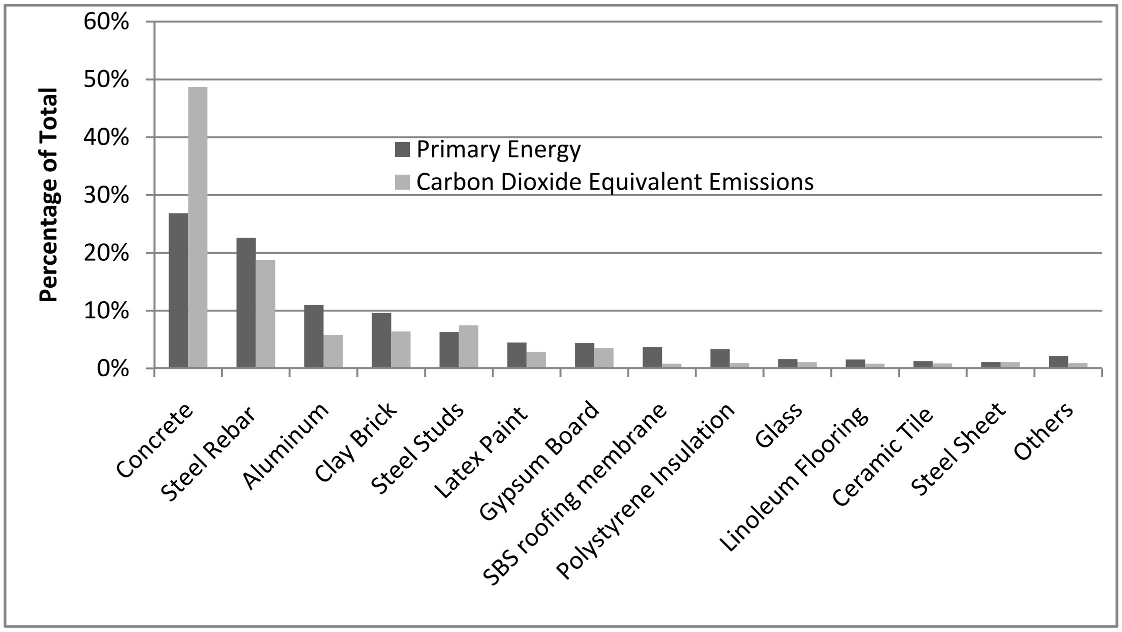

Figure 5.6: Allocation of PE consumption and CO_2e Emissions to Building Products

Environmental burdens per product can be aggregated to the structural and envelope assemblies and envelope-related interior finishings. Results of such aggregation are shown in Figure 5.7.

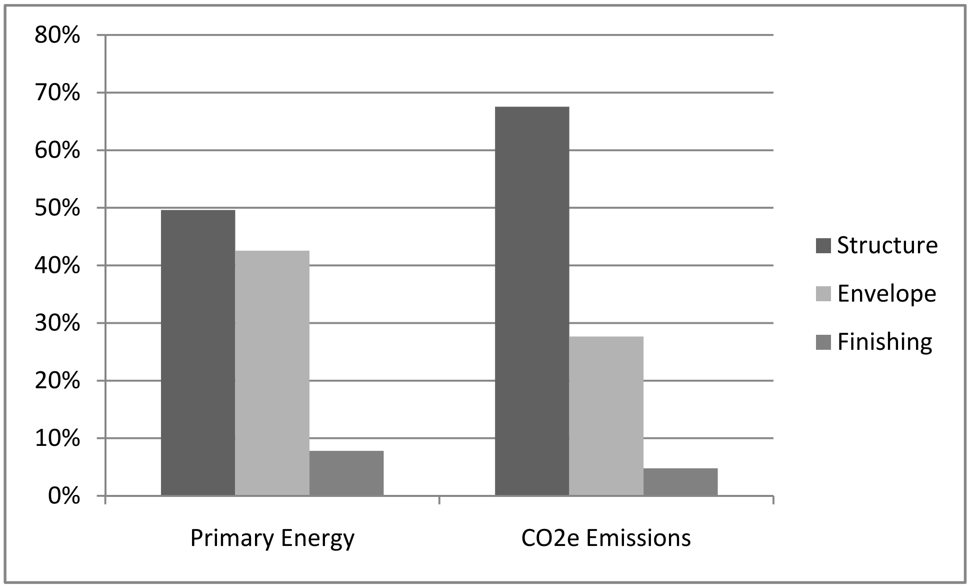

Figure 5.7: Allocation of PE consumption and CO_2e Emissions to Building Assemblies

5.5 Summary

Due to its complete, convenient and consistent accounting of upstream processes, PMR-based LCI is selected as the most qualified methodology to be used for further analysis in this study. Using this methodology, environmental burdens of 4.45 GJ PE/m^2 and 317 kg CO$_2$e/m^2 are calculated. These results compare well with those found in other studies. Embodied to annual operational PE consumption and CO$_2$e emissions ratios are 1.86 and 5.20, respectively. The former ratio is low compared to other studies. The latter ratio compares well. The structure, envelope, and interior finishings account for 49.6%, 42.6% and 7.8% of overall PE consumption, respectively, and 67.6%, 27.7% and 4.8% of CO$_2$e emissions, respectively.

6 ANALYSIS OF LEED CRITERIA

In this chapter, PMR-based LCI data for the Medical Sciences Building (MSB) are used to assess the efficacy of LEED reused, recycled and regional product criteria in promoting the reduction of PE consumption and CO_2e emissions (herein referred to as 'environmental burdens'). Summaries are given and LCI data are developed for both the reused and recycled products used in the MSB. Reductions of environmental burdens due to the use of reused and recycled products are then quantified. Due to lack of available transport data, reductions of environmental burdens due to the use of regional products could not be quantified. Instead, general transport requirements for each product are rated.

6.1 Reused Product Analysis

In this section, the dollar value (herein referred to as 'value') of each reused product in the MSB is first listed. LCI data development methodologies for reused products are then described. Using the LCI data, the overall reduction of environmental burdens due to the specific selection of reused building products in the MSB are calculated. Indeed, overall reductions of environmental burdens depend significantly on the types of products being reused. To illustrate this point, product selection scenarios are modeled that maximize and minimize reductions of environmental burdens while keeping the overall value of reused products in the MSB constant. These scenarios are presented at the end of this section.

6.1.1 Reused Product Summary

Table 6.1 lists reused building products identified in the MRP and considered in this analysis (TBKG, 2004). Any products listed in the MRP not included within the system boundary for this study are excluded from analysis. Further, several building products within the system boundary are not explicitly identified in the MRP, namely steel nails, steel screws/nuts/bolts, EPDM rubber, vinyl flooring and asphalt. These products are also excluded from analysis.

Table 6.1: Reused Product Summary for MSB

Building Product	**Total Value**	**Percentage Reused**	**Reused Value**
Sand and Gravel	$70,000	50.0%	$35,000
Concrete	$393,480	4.7%	$18,624
Steel Rebar	$210,000	5.0%	$10,500
Clay Brick	$115,000	7.0%	$8,050
Aluminum	$114,000	7.0%	$7,980
Steel Studs	$98,138	5.0%	$4,907
Window Glass	$98,000	5.0%	$4,900
Gypsum Board	$90,150	5.0%	$4,508
Latex Paint	$48,080	2.0%	$962
SBS Membrane	$22,326	3.7%	$815
Linoleum Flooring	$75,247	1.0%	$752
Polystyrene Insulation	$25,920	2.0%	$518
Fiberglass Insulation	$15,829	3.0%	$475
Polypropylene Membrane	$18,280	2.0%	$366
Steel Sheet	$33,000	1.0%	$330
Nylon Carpet	$31,500	1.0%	$315
Ceramic Tile	$19,240	1.0%	$192
Polyethylene Vapour Barrier	$4,845	2.0%	$97
Total	**$1,567,813**	**6.3%**	**$99,291**

6.1.2 LCI Data Development

LCI data for reused products are developed using the following methodology:

a) Cost percentages of reused products listed in Table 6.1 are applied to physical quantities of building products in the MSB.

b) Closed-loop reuse is assumed (i.e. products are reused for the same purpose as their original use). Additional energy is typically required in building disassembly when products are salvaged for reuse. However, energy input data could only be found for concrete and steel structure salvaging (M. Gordon Engineering, 1997). To treat all products equivalently, no additional energy inputs are considered for any product.

c) Due to unavailable transport data for reused products from a previous building site to a distribution centre, transport inputs to reused product unit processes are assumed equal to those in the *base case* scenario (i.e. product manufactured from 100% virgin materials).

6.1.3 Results

Overall reductions of environmental burdens through the specific selection of reused products in the MSB are listed in Table 6.2 and illustrated in Figure 6.1. PE consumption and CO_2e emissions are reduced by 819 GJ (4.4%) and 59 tonnes (4.5%), respectively.

Table 6.2: Total Environmental Burdens for Reused and Base Case Scenarios

			Reductions	
	Reuse Scenario	**Base Case Scenario**	**Absolute Value**	**Percentage**
PE Consumption (GJ)	**17,381**	**18,201**	**819**	**-4.4%**
Natural Gas	6,612	6,925	313	-4.5%
Crude Oil	3,767	3,900	133	-3.4%
Bituminous Coal	2,480	2,602	123	-4.7%
Sub-bituminous Coal	764	806	42	-5.3%
Lignite Coal	272	287	15	-5.2%
Uranium Oxide	1,745	1,842	97	-5.3%
Hydropower	1,743	1,839	97	-5.3%
CO_2e emissions (tonnes)	**1,238**	**1,297**	**59**	**-4.5%**

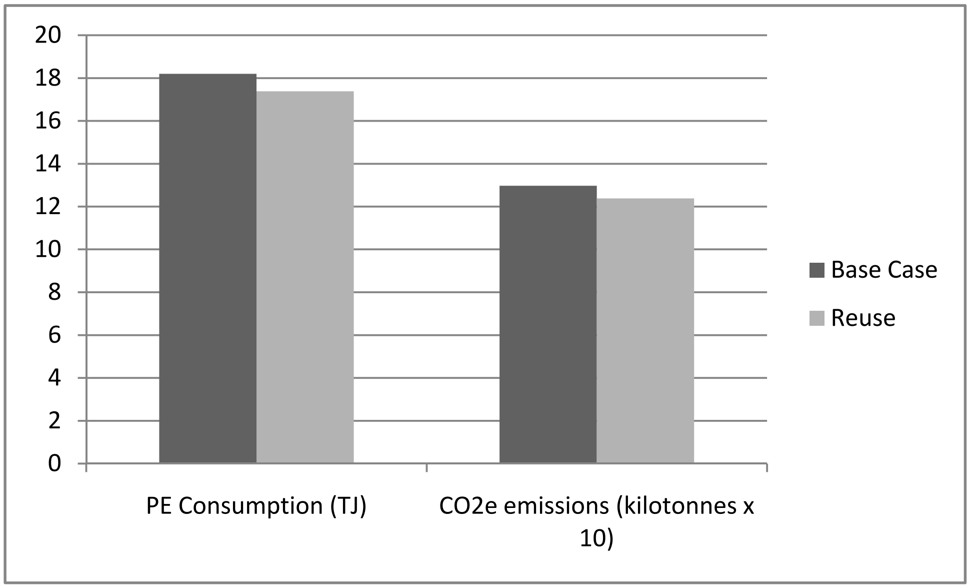

Figure 6.1: Total Environmental Burdens for Reused and Base Case Scenarios

Total reduction of environmental burdens can be attributed to individual reused products, as shown in Figure 6.2. For example, the reuse of $18,624 of concrete accounts for 50% of total CO_2e reductions (i.e.

30 of 59 tonnes). In particular, the values of reused concrete, steel rebar, aluminum, clay brick and steel studs in the MSB account for 85.4% of PE reductions and 91.6% of CO_2e emission reductions. These five products, however, account for only 50.9% of the total value of reused products in the MSB. The reason for such a discrepancy between percentage value of reused product and percentage reduction of environmental burdens is simple: The reduction of environmental burdens per unit value of reused product depends significantly on the type of product being reused.

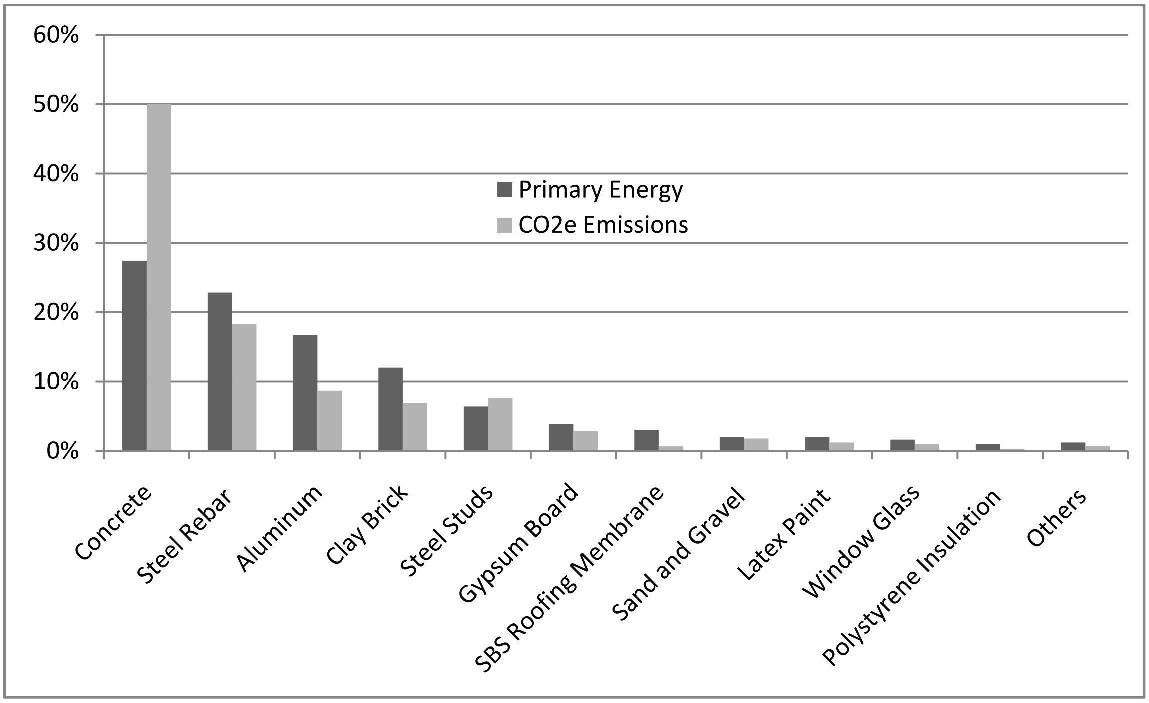

Figure 6.2: Allocation of Overall Environmental Burden Reductions to Reused Products

The reduction of environmental burdens per \$1000 of each reused product in the MSB is shown in Figures 6.3 and 6.4 for PE consumption and CO_2e emissions, respectively. As seen in the Figures, the range in reductions among products is wide: 0.2 to 30 GJ PE/\$1000 and 7 to 1,577 kg CO_2e/\$1000. On average, the specific selection of reused products in the MSB results in reductions of 8.2 GJ PE/\$1000 and 590 kg CO_2e /\$1000. These are labelled ‘MSB Average’ in Figures 6.3 and 6.4.

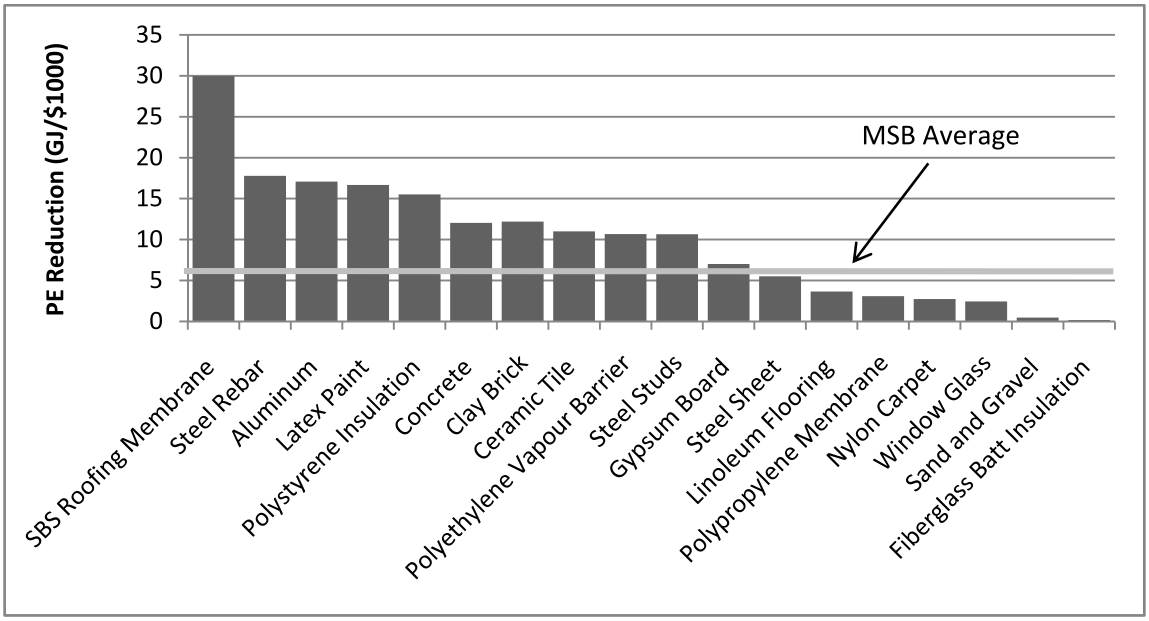

Figure 6.3: Reductions in PE Consumption per $1000 of Reused Product

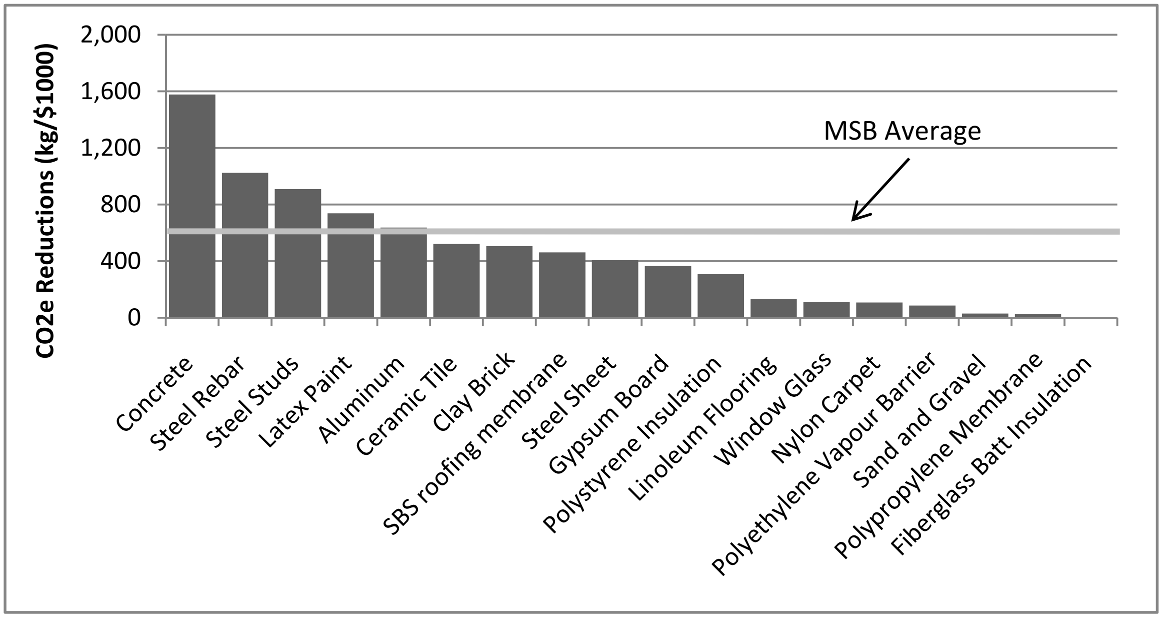

Figure 6.4: Reductions in CO_2e Emissions per $1000 of Reused Product

In general, then, the average reduction of environmental burdens per $1000 of reused product depends significantly on the specific selection of products. If a higher proportion of products on the left sides of Figures 6.3 and 6.4 are selected (i.e. steel, aluminum, etc.), the average will increase. If a higher proportion of products on the right sides of Figures 6.3 and 6.4 are selected (i.e. fiberglass insulation, sand and gravel, etc.), the average will decrease.

Indeed, there are limits within which the average reduction of environmental burdens per $1000 reused product may vary. The maximum results from reusing *only* the leftmost products of Figures 6.3 and 6.4. The minimum results from reusing *only* the rightmost products of Figure 6.3 and 6.4. In both cases, the total value of reused product in the MSB is kept constant at $99,291, the same value of actual reused products in the MSB. The only constraint applies to reused concrete, which can only be used in a select number of applications (M. Gordon Engineering, 1997). Thus, it is assumed that the $18,624 of reused concrete (4.7% of total concrete value) in the MSB is the maximum attainable reused value. For the remainder of products, it is assumed that 100% reuse is attainable.

Figure 6.5 illustrates the actual, maximum and minimum reductions of environmental burdens per $1000 of reused product that are attainable in the MSB. Reductions of PE consumption range between 0.7 and 18.8 GJ/$1000 reused product. Reductions of CO_2e emissions range between 25 and 1,113 kg CO_2e/$1000 reused product.

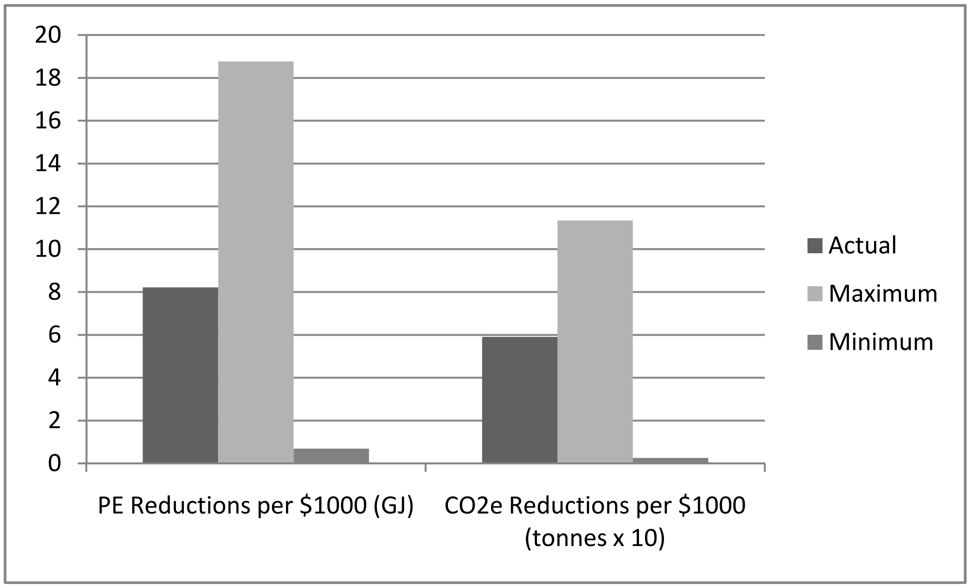

Figure 6.5: Range of Reductions of Environmental Burdens per $1000 of Reused Product

These ranges are impermissibly large. LEED reused product criteria are meant to reduce the “impacts resulting from extraction and processing of virgin materials” (USGBC, 2005). However, as illustrated in Figure 6.5, adherence to the criteria in no way ensures a consistent reduction of environmental burdens. Indeed, in the minimum case, the reduction is nearly negligible.

6.2 Recycled Product Analysis

In this section, the value of each recycled product in the MSB is first listed. LCI data development methodologies for recycled products are then described. Using the LCI data, the overall reduction of environmental burdens due to the specific selection of recycled building products in the MSB are calculated. Indeed, the overall reduction of environmental burdens depends significantly on the types of product being recycled. To illustrate this point, product selection scenarios are modeled that maximize and minimize reductions of environmental burdens while keeping the overall value of recycled products in the MSB constant. These scenarios are presented at the end of this section.

6.1.1 Recycled Product Summary

Table 6.3 lists recycled building products identified in the MRP and considered in this analysis. Again, all recycled building products listed in the MRP that are not included within the LCA system boundary for this study are excluded from analysis. In addition, steel recycling and fly ash substitution in concrete are excluded since both practices are status-quo in the construction industry. Structural steel typically incorporates 90-95% recycled steel (MES, 2002) while fly ash typically supplements 10% of cement in concrete (CCMET, 1999). Base case LCI data for steel and concrete already account for these practices. Thus, the related reductions of environmental burdens have already been attributed to the MSB.

Table 6.3: Recycled Product Summary for the MSB

Building Product	**Total Value**	**Percentage Recycled**	**Value Recycled**
Concrete	$393,480	14.8%	$58,089
Aluminum	$114,000	45.0%	$51,300
Linoleum Flooring	$75,247	40.0%	$30,099
Window Glass	$108,000	25.0%	$27,000
Polystyrene Insulation	$38,670	65.9%	$25,475
Gypsum Board	$90,150	20.0%	$18,060
Clay Brick	$115,000	10.0%	$11,500
Fiberglass Insulation	$15,829	27.0%	$4,274
Polypropylene Membrane	$18,280	20.0%	$3,656
SBS Roofing Membrane	$22,326	9.0%	$2,010
Plywood	$22,028	5.0%	$1,101
Total	**$1,567,813**	**14.8%**	**$232,564**

6.2.2 LCI Data Development

LCI data for recycled products must account for the energy consumed in the recycling process. Open-loop recycling is assumed (i.e. original product is recycled for different use) since LCI data for recycling is not specific to building products. Similar to the reused product analysis, transportation inputs to recycled product unit processes are assumed equal to the base case.

Two different recycling scenarios are modeled. For some building products (e.g. plastics), a recycled product is manufactured separately from its equivalent base case product. For other building products (e.g. concrete), the recycled product is reintegrated into the base case manufacturing process to supplant the use of virgin resources. The quality and availability of energy input data for recycling varies for each product. Thus, a standardized methodology is used to quantify energy inputs to recycled product unit processes for each recycling scenario. This methodology is described in Table 6.4. LCI data for each recycled building products are listed in Appendix L.

Table 6.4: Unit Process Development Methodologies for Recycled Products

Building Product	**Unit Process Development Methodology**
<u>Separate Manufacturing</u> Aluminum Fiberglass insulation Plywood Polypropylene membrane Polystyrene SBS roofing membrane Window Glass	• Calculate energy input ratio between base case and recycled product manufacturing per unit mass of product • Apply ratio to each energy input in base case unit process to calculate energy inputs for recycled product unit process • Omit all non-energy inputs except transportation in recycled product unit process
<u>Reintegrated Manufacturing</u> Concrete Clay Brick Gypsum Board Linoleum Flooring	• Equate all energy inputs to base case unit process • Omit all non-energy inputs except transportation in recycled product unit process • Include energy inputs in recycled product unit process that account for crushing of recycled product for reintegration into new product manufacturing

6.2.3 Results

Overall reductions of environmental burdens through the specific selection of recycled products in the MSB are listed in Table 6.5 and illustrated in Figure 6.6. PE consumption and CO_2e emissions are reduced by 1,846 GJ (10.1%) and 126 tonnes (9.7%), respectively.

Table 6.1: Total Environmental Burdens for Recycled and Base Case Scenarios

	Recycling Scenario	Base Case Scenario	Reductions	
			Absolute Value	Percentage
PE Consumption (GJ)	**16,355**	**18,201**	**1,846**	**-10.1%**
Natural Gas	6,220	6,925	705	-10.2%
Crude Oil	3,449	3,900	451	-11.6%
Bituminous Coal	2,400	2,602	202	-7.8%
Sub-bituminous Coal	723	806	83	-10.2%
Lignite Coal	257	287	30	-10.2%
Uranium oxide	1,653	1,842	189	-10.2%
Hydropower	1,651	1,839	188	-10.2%
CO_2e emissions (tonnes)	**1,171**	**1,297**	**126**	**-9.7%**

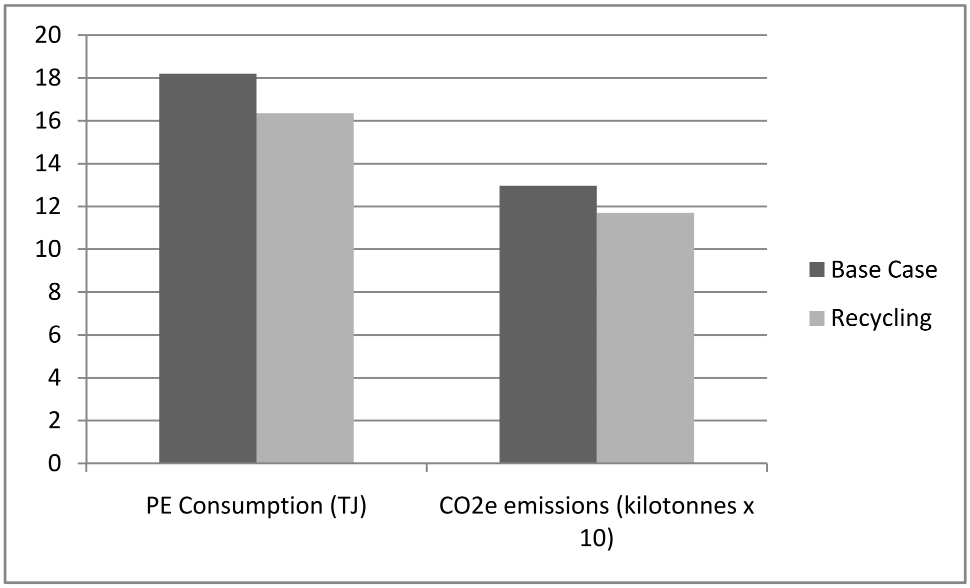

Figure 6.6: Total Environmental Burdens for Recycled and Base Case Scenarios

Total reduction of environmental burdens can be attributed to individual recycled products, as shown in Figure 6.7. For example, the recycling of $58,089 of concrete accounts for nearly 70% of total CO_2e reductions (87 of 126 tonnes). In particular, the recycling of concrete, aluminum and polystyrene insulation in the MSB account for 92.2% of PE reductions and 96.0% of CO_2e emission reductions. These three products, however, account for only 60.0% of the total value of recycled products in the MSB. The reason for such a discrepancy between percentage value of recycled product and percentage reduction of environmental burdens is simple: The reduction of environmental burdens per unit value of recycled product depends significantly on the type of product being recycled.

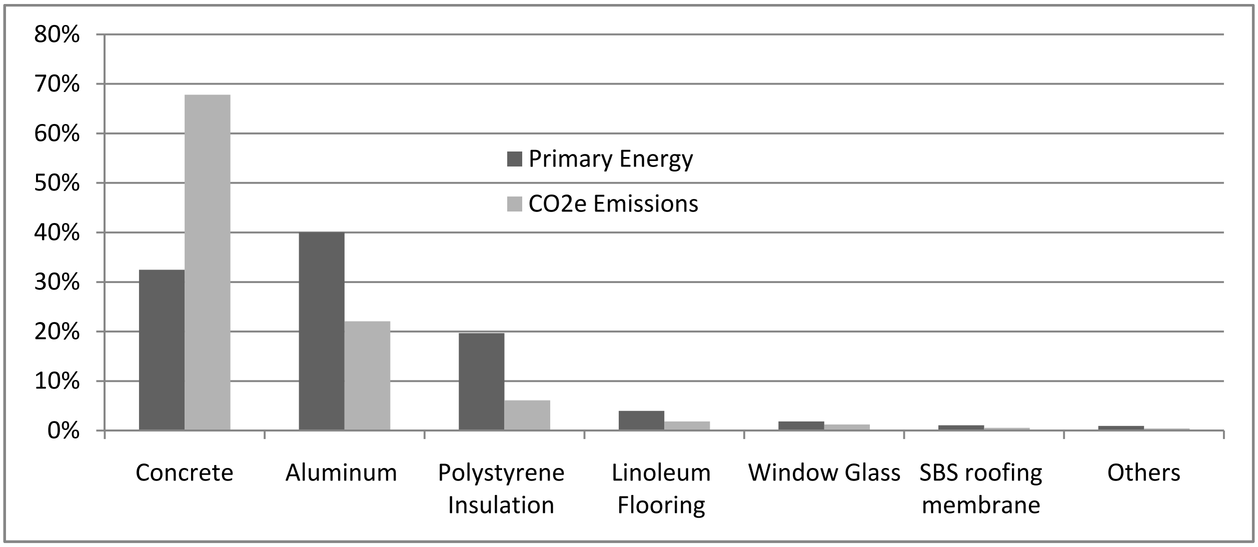

Figure 6.7: Allocation of Overall Environmental Burden Reductions to Recycled Products

The reduction of environmental burdens per \$1000 of each recycled product in the MSB is shown in Figures 6.8 and 6.9 for PE consumption and CO_2e emissions, respectively. As seen in the Figures, the range in reductions among products is wide: 0.09 to 14.4 GJ PE/\$1000 and 4 to 1,474 kg CO_2e /\$1000. On average, the specific selection of recycled products in the MSB results in reductions of 6.11 GJ PE/\$1000 and 543 kg CO_2e /\$1000 of recycled product. These are labelled 'MSB Average' in Figures 6.8 and 6.9.

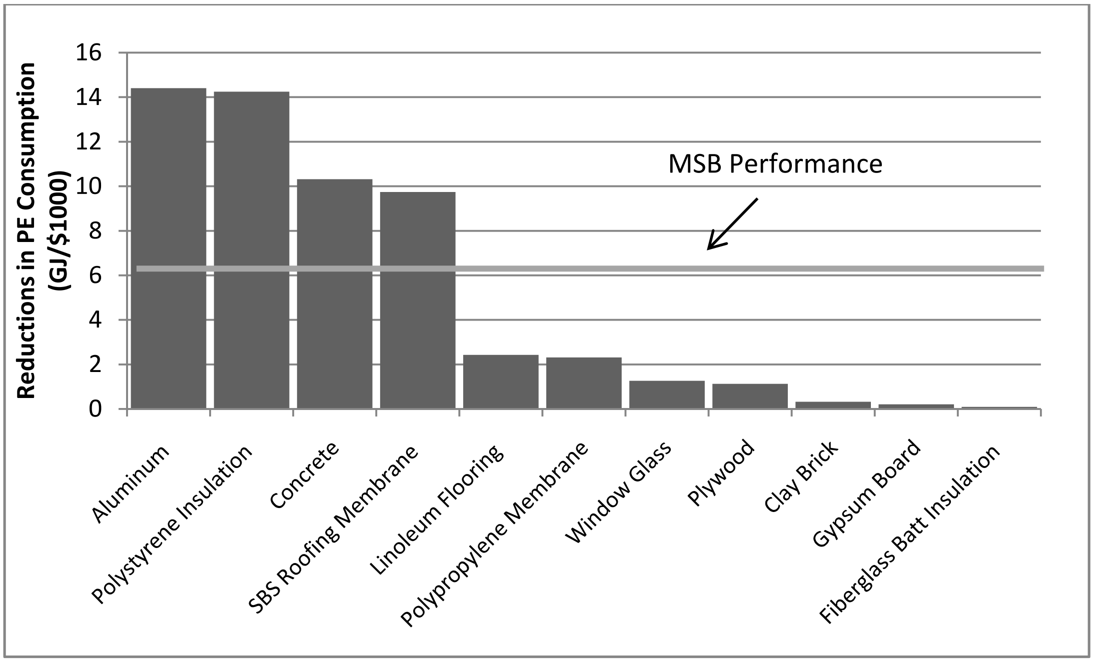

Figure 6.8: Reductions in PE Consumption per $1000 of Recycled Product

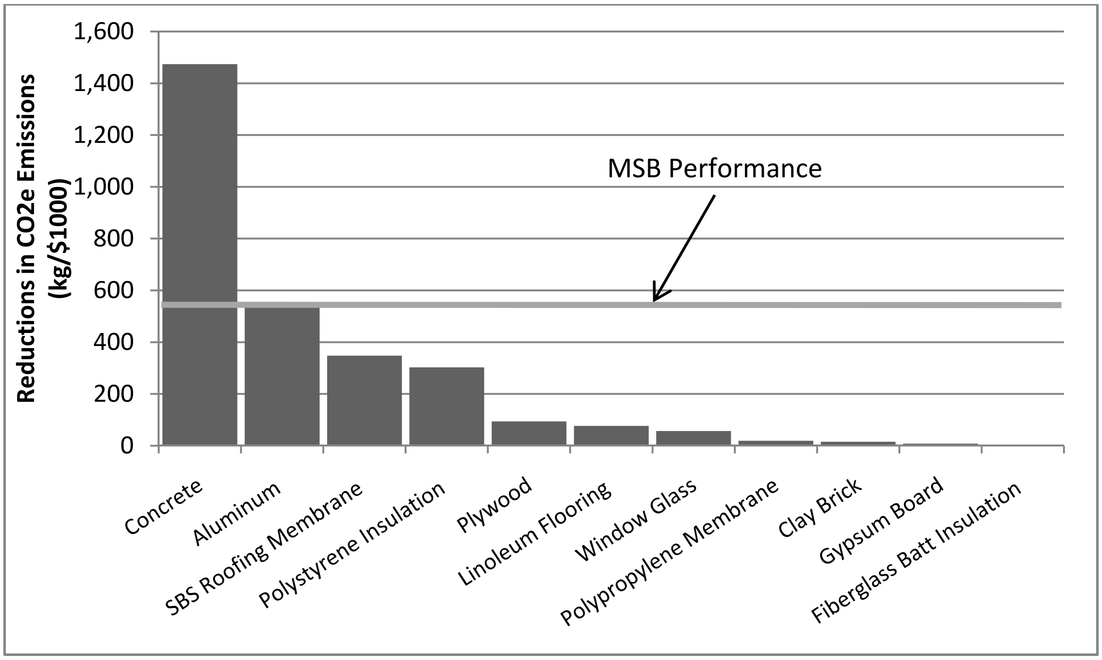

Figure 6.9: Reductions in PE Consumption per $1000 of Recycled Product

In general, then, the average reduction of environmental burdens per $1000 of recycled product depends significantly of the specific selection of products. If a higher proportion of products on the left sides of Figures 6.8 and 6.9 are selected (i.e. concrete, aluminum, etc.), the average will increase. If a higher proportion of products on the right sides of Figures 6.8 and 6.9 are selected (fiberglass insulation, gypsum board, etc.), the average will decrease.

Indeed, there are limits within which the average reduction of environmental burdens per $1000 recycled product may vary. The maximum results from recycling *only* the leftmost products of Figures 6.8 and 6.9. The minimum results from recycling *only* the rightmost products of Figure 6.8 and 6.9. In both cases, the total value of recycled product in the MSB is kept constant at $232,564, the same value of actual recycled products in the MSB. The only constraint applies to concrete, which cannot incorporate more than 25% recycled material (M. Gordon Engineering, 1997). Thus, it is assumed that 25% of total concrete value (i.e. $98,370 of $393,480) is the maximum recycled value. For the remainder of products, it is assumed that 100% recycled content is attainable.

Figure 6.10 illustrates the actual, maximum and minimum reductions of environmental burdens per $1000 of recycled product that are attainable in the MSB. The range in reduction of PE consumption is between 0.3 and 12.5 GJ/$1000 recycled product. The range in reduction of CO_2e emissions is between 12 and 918 kg CO_2e/$1000 recycled product.

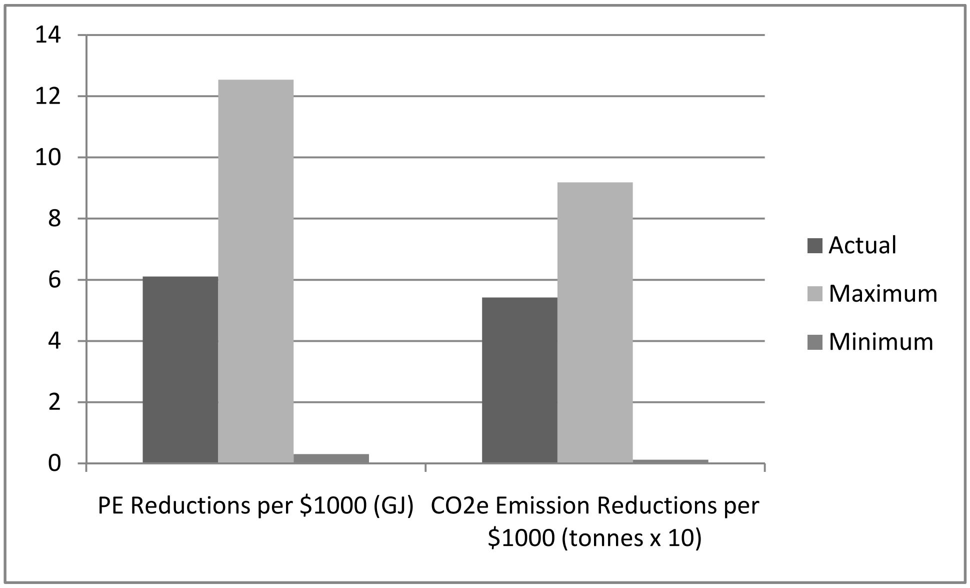

Figure 6.10: Range of Reductions of Environmental Burdens per $1000 of Recycled Product

These ranges are impermissibly large. LEED recycled product criteria are meant to reduce the “impacts resulting from extraction and processing of virgin materials” (USGBC, 2005). However, as illustrated in

Figure 6.10, adherence to the criteria in no way ensures a consistent reduction of environmental burdens. Indeed, in the minimum case, the reduction is nearly negligible.

6.3 Regionally Extracted and Manufactured Products

LEED submission data for regional products indicate only if a product and its constituent materials are manufactured and extracted within 800km and do not indicate actual distances. Thus, reductions of environmental burdens through the use of regional products cannot be quantified. Instead, the mass of each building product is quantified per $1000 value, as shown in Figure 6.11. A higher ratio indicates increased transportation requirements and thus increased environmental burdens. Ratios for sand, gravel and concrete are significantly higher than all other products and are thus listed and not plotted in Figure 6.11.

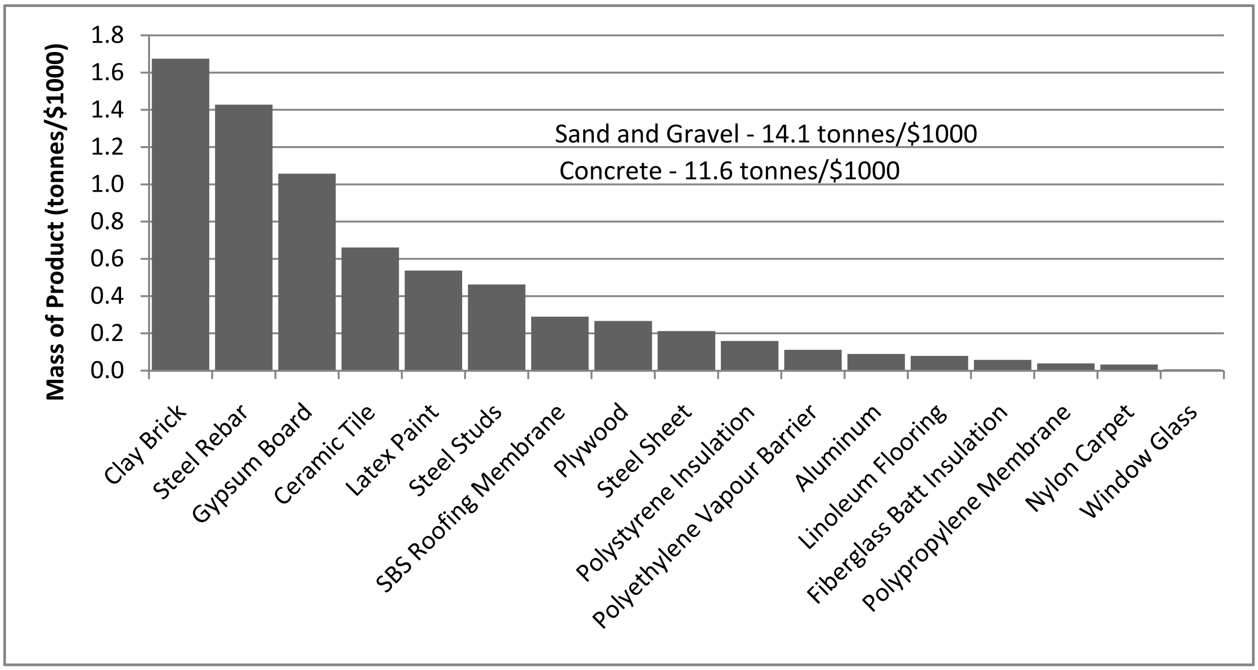

Figure 6.11: MSB Product Mass per $1000

The range in mass to value ratios amongst the products is large. Thus, the range of environmental burdens associated with the transport of these products is also large. However, LEED criterion for regional products requires that only a total value of products are obtained regionally and does not account for the range in transport requirements of different products. Thus, adherence to the criteria does not ensure a consistent reduction of environmental burdens. Indeed, by selecting only the rightmost products in Figure 6.11 to be obtained regionally, the reduction of environmental burdens is nearly negligible.

6.4 Overall Reductions

The combined use of reused and recycled products results in an overall reduction of environmental burdens for the MSB. Depending on the choice of products to be reused or recycled, the reduction can be significant or nearly negligible. Figure 6.12 illustrates the overall environmental burdens of the MSB given four environmental burden reduction scenarios: base case (no reuse or recycling), actual, maximum and minimum. All scenarios except the base case use constant values of reused ($99,291) and recycled ($232,564) products. Compared to the base case, actual reduction of environmental burdens are 2,666 GJ PE (14.6%) and 185 tonnes CO_2e emissions (14.3%). Maximum reductions are 4,779 GJ PE (26.2%) and 326 tonnes CO_2e emissions (25.2%). Minimum reductions are 174 GJ PE (1.0 %) and 7 tonnes CO_2e emissions (0.5%).

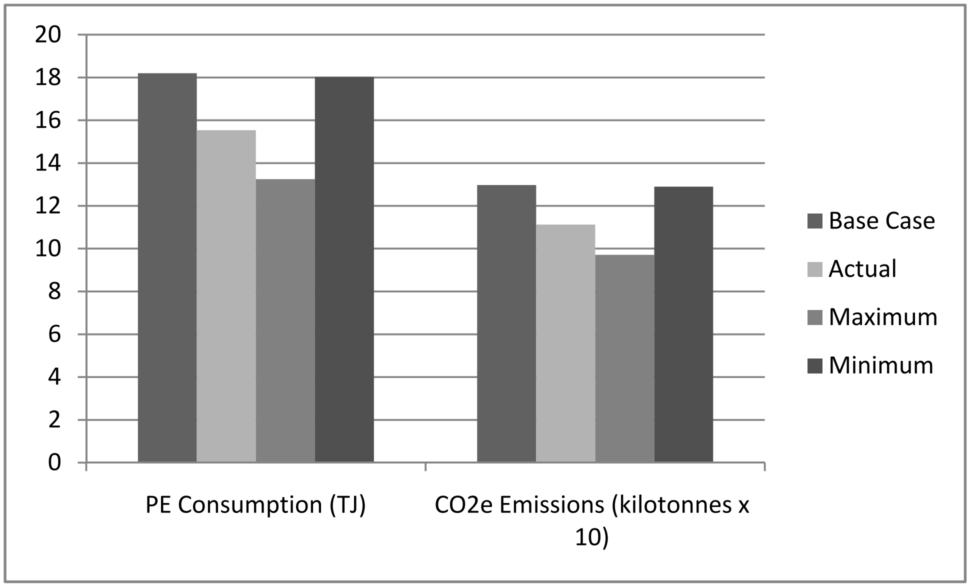

Figure 6.12: Overall Environmental Burden Scenarios for the MSB

6.5 Summary

Specific types and values of products were selected to meet LEED criteria for reused, recycled and regional products. The particular selection of products for each criterion has significant influence on the overall reduction of environmental burdens. Such reductions can not be quantified for regional product selections due to unavailable data. However, such reductions for reused and recycled product are quantified and the results are conclusive. Given constant reused and recycled product values that are sufficient to meet each criterion, the possible selection of products allows an impermissible range of overall reductions of environmental burdens: 1.0% to 26.2% for PE consumption and 0.5% to 25.2% for CO_2e emissions. Adherence to the criteria, then, may result in a nearly negligible reduction of environmental burdens.

7 DISCUSSION

In this chapter, study results obtained in Chapter 5 and 6 are discussed. First, the state of public LCI data applicable to Canada is discussed. Next, the benefits and drawbacks of the three LCI methodologies and the difficulties in developing LCI data in general are discussed. Next, the efficacy of LEED reused, recycled and regional criteria in promoting a consistent reduction of environmental burdens is discussed. Finally, modifications to current criteria are proposed and alternate environmental burden-based criteria that stipulate overall reductions of environmental burdens are explored.

7.1 State of Public LCI Data

A comprehensive public LCI database specific to a wide range of geographical areas is a prerequisite for LCA incorporation into LEED. However, poor LCI data availability and transparency within Canada, and to a lesser extent within the U.S., are presently major impediments to such incorporation.

To begin, there are no adequate public LCI data applicable to Canada. The Canadian Raw Materials Database is public, but has very few products applicable to building construction and does not provide adequately detailed inputs for each unit process within the product system. The only remaining Canadian-based LCI data are those compiled by the ASMI. Such data, however, are not publicly available and are deficient in several areas. First, data are not available for flooring products, polypropylene and plywood. Second, data for several products (aluminum, polyethylene vapour barrier, polystyrene insulation and SBS roofing membrane) do not provide adequately detailed inputs for each unit process and thus were not used in this study. Other data were equally inadequate (steel products, fiberglass insulation and window assemblies) but due to a lack of other applicable data sources, these data were modified for use in this study using the assumptions described in Appendix G. These assumptions introduce some uncertainty in results.

Due to unavailable Canadian-based LCI data, other data sources were used. The U.S-based NREL database was the principal alternate data source. NREL LCI data were complete (i.e. all life cycle stages were included) and sufficiently transparent. However, data were not available for the following products: several non-energy resources (i.e. sand and gravel, clay, gypsum and iron), styrene-butadiene polymer, fiberglass insulation, titanium dioxide, latex paint and all flooring products. The U.S-based BEES LCI database provided data for some of these products, yet insufficient transparency within the data required the use of the Swedish CPM database to model select products. Non-energy resources were modeled using Canadian national statistical survey-based data. The use of foreign data and national statistics introduces some uncertainty in results.

Transport data for many products were unavailable, unclear, or unjustified. In particular, ASMI data for several products fail to indicate whether transportation inputs are included within the product system. The inclusion of transport inputs was equally inconsistent within the BEES LCI database. When transport inputs were indicated, they were often based on unjustified estimations. NREL data, on the other hand, consistently and transparently accounted for all transport inputs.

In place of the missing transport inputs, national statistical data for several transport industries were used. Such data, however, are highly aggregated and it is uncertain to what extent they accurately represent transport inputs.

Finally, adequate data for recycled product manufacturing were unavailable for North America. This data gap is particularly problematic since the comparative assessment of environmental burdens between recycled and base case products relies on accurate recycling data. All of the data used are from foreign sources (i.e. China, Japan and Sweden) and may be based on different processes and technologies than those found in North America. Types of fuel inputs were modified to better resemble typical manufacturing fuels within North America. Such modifications, however, introduce some uncertainty in results.

Given these various deficiencies, it is clear that LCI data are underdeveloped and cannot presently be incorporated into LEED. To overcome these deficiencies, LCI data must first be developed for significantly more products manufactured in North America. Second, LCA practitioners must use more diligence in abiding by ISO 14040 transparency requirements. The lack of sufficient transparency for otherwise regionally applicable data is a major but easily remedied impediment.

Given the various sources of uncertainty in this study, estimations of environmental burdens may be inaccurate. Such inaccuracy, however, is difficult to quantify given the lack of an established uncertainty analysis component to LCA.

7.2 Comparison of LCI Methodologies

Due to the additional time requirements and inconsistent accounting of upstream processes, PS-based LCI is both inconvenient and incomplete. That it is the most widely used LCI methodology can perhaps be attributed to its underestimation of environmental burdens, which may be a desirable feature from the perspective of the facility of company conducting an LCA for their product.

Due to industry aggregation and data gaps, I/O-based LCI calculates environmental burdens with a high degree of uncertainty and in most cases will not provide a reliable estimation of environmental burdens. Rather, I/O-based LCI provides only a general indication of environmental burdens.

PMR-based LCI, on the other hand, accounts for all upstream processes within a convenient and consistent mathematical framework. For these reasons, PMR-based LCI should replace PS-based LCI as the most common methodology used by LCA practitioners. Indeed, PMR-based LCI should become the ISO 14041 standard methodology for use in LCA studies. A consistent methodology for all LCA studies will provide more meaningful comparisons between the environmental performances of products.

7.3 Correlating Physical to Cost Units

Results in this study depend to a large extent on the proper correlation of product quantities to costs. In this study, two entirely separate documents were used to develop quantity and cost: the pre-tender estimate report and the MRP, respectively. The two documents, however, do not always provide unambiguous correlations between products. For instance, vinyl flooring is listed in the pre-tender estimate but not in the MRP report. It can only be presumed that the product was removed from final design plans after the pre-tender estimate was released. In addition, inadequate descriptions of certain products within the MRP (e.g. spray insulation) make the correlation between quantity and cost somewhat ambiguous. Assumptions were made in these cases, potentially introducing uncertainty in results. Uncertainty in this case is particularly problematic since the ratios between quantity and cost are critical in the comparative assessments made in Chapter 6 for reused, recycled and base case products. To improve the accuracy of LCA results for buildings, there must be better correlation between product quantity and cost. For example, a summary document listing both quantity and cost of each building product would eliminate the uncertainties encountered in this study.

7.4 Efficacy of LEED Criteria

As demonstrated in this study, reductions of environmental burdens per unit value of product are unique to each product. Thus, current cost-based percentage requirements for reused, recycled and regional products are ineffective in the consistent reduction of environmental burdens. LCA can be used in the short-term to modify criteria to promote a more consistent reduction of environmental burdens. LCA can also be used in the long-term to develop environmental burden-based criteria that ensure a consistent and measurable reduction of environmental burdens.

7.4.1 Modifications to Current Criteria

Cost-based percentages can be maintained provided that the products with the highest environmental burdens per unit cost are addressed in separate criteria. Recommendations made in this section apply specifically to reductions in PE consumption and CO_2e emissions only. The consideration of other environmental burdens, of course, will result in different product recommendations. Table 7.1 lists several products which should be addressed through separate reused, recycled and regional product criteria.

Table 7.1: Building Products that Require Separate Environmental Performance Criteria

Reused Product	**Recycled Product**	**Regional Product**
Aluminum	Aluminum	Concrete
Concrete	Concrete	Sand and Gravel
Latex paint	Polystyrene insulation	
Polystyrene insulation	SBS roofing membrane	
SBS roofing membrane	All steel products	
Steel rebar	Fly ash	

Building products not listed in Table 7.1 should still meet an overall percentage of reused, recycled and regional content. This requirement will maintain market demand for the increased environmental performance of *all* building products, and not solely those attributed with the highest PE consumption and CO_2e emissions.

Actual percentage requirements (10% reused, 20% recycled, etc.) for each product depend on several factors. First, the market availability of reused, recycled and regional products may be a limitation. Second, changes to the physical properties of a product due to reused or recycled content are also limitations. In particular, the strengths of reused concrete, recycled concrete and reused steel are all reduced compared to the base case (M. Gordon Engineering, 1997). Third, a consensus within the building industry as to what constitutes an adequate reduction of environmental burdens will largely determine percentage requirements. The Government of British Columbia has mandated a 33% reduction in CO_2e emissions in the province by 2020 (Office of the Premier, 2007). An equivalent target could be adopted into the LEED criteria, where percentages of reused, recycled and regional products are defined in such a way to achieve an overall 33% reduction in CO_2e emissions.

In particular, the recycling of all steel products and the use of fly ash in concrete should also be addressed in separate criteria. Due to the large quantities of steel and concrete in buildings, these status-quo recycling practices are often sufficient on their own to meet LEED criteria, thus discouraging the recycling of other products. Required percentages within the criteria for recycled steel and fly ash should be greater than current status-quo practices. Steel can be 100% recycled (MES, 2002). Fly ash can supplement up to 30% of cement, though at these high percentages the strength of concrete decreases and its uses are limited (Kelly, 1998)

Further research is needed to accurately quantify the useful lives of reused and recycled products relative to base case products. Generally, reused and recycled products exposed to the interior (e.g. flooring, paint, etc.) and the exterior (e.g. roofing membranes) require more frequent replacement than base case products. More frequent replacement results in increased environmental burdens. Thus, the development of reused and recycled product criteria should consider both initial and life cycle environmental burdens over the service life of the building. If the increase in life cycle environmental burdens exceeds the initial decrease in environmental burdens, then the product should not be reused or recycled.

These proposed modifications to reused, recycled and regional product criteria slightly increase the complexity of the certification process since several additional criteria must be considered. However, such additions do not increase the time requirements of the certification process since the environmental performance of all building products is already taken into account within current LEED criteria. The only difference between the current and proposed certification processes is the particular criterion to which each product is applied.

7.4.2 Environmental Burden-based Criteria

Provided that LCI data are sufficiently comprehensive and regionalized, the reduction of environmental burdens through the use of reused, recycled and regional products can be calculated with accuracy. If an adequate level of LCI data quality is attained in the future, then environmental burden-based LEED criteria can be developed that stipulate an overall reduction of environmental burdens without requiring mandatory percentages of reused, recycled or regional products. Rather, any combination of these products would be permissible provided the criteria are met. Examples of such criteria include a 15% reduction in CO_2e emissions compared to a base case scenario or 2 L of crude oil or less consumed per m^2 of building. A contractor or architect would specify total product quantities, reused and recycled percentages and origins of building products, and LCA-based software would calculate overall reduction of environmental burdens. If needed, these variables would be modified until the criteria are met.

Such a procedure is relatively simple when selecting products to meet a single criterion or mutually dependent criteria (e.g. PE consumption and CO_2e emissions). However, given several potentially diverse criteria (e.g. acidification and eutrophication), there may only exist a finite number of product combinations that will meet all criteria. Thus it may be difficult for the user to determine a suitable combination of products. As discussed in Chapter 3, such difficulties are undesirable for a rating system or eco-label.

Such difficulties can be avoided through the use of optimization models, which consist of an objective function and a set of constraints expressed within a system of equations or inequalities. Such models are used to determine an optimal solution, typically the minimization or maximization of a particular variable. Optimization can thus be used to select the optimum combination of building products that meet or exceed environmental burden-based criteria.

Identifiable constraints would include total product quantities, the maximum percentage of reused and recycled products available for the project and environmental burden-based criteria. The objective function can be any number of variables. In the simplest case, the objective function could be a specific environmental burden for which criterion already exists (e.g. CO_2e emissions). The optimum product combinations would then be selected such that the particular criterion is not only met, but that the environmental burden it addresses is minimized.

Alternatively, the *life cycle* environmental burdens of the building can be minimized. Many reused and recycled products have shorter life spans and need to be replaced more frequently than base case products. Over the life cycle of a building, then, the use of reused and recycled products may ultimately result in increased environmental burdens. Optimization can be used to minimize life cycle environmental burdens while ensuring that all criteria are still met.

Similarly, the initial or life cycle cost of building products could be minimized. Reused and recycled products may be more or less expensive than their base case equivalent, depending on the type of product. Moreover, the increased frequency of replacement of reused and recycled products increases the maintenance costs of the building. Optimization can be used to minimize either the initial or life cycle cost of building products while ensuring that all criteria are still met.

A meaningful demonstration of optimization applications within the proposed criteria requires reliable data pertaining to the availability of reused and recycled building products in addition to their life spans and costs relative to base case products. Such data could not be found for most building products. Thus, optimization is not demonstrated in this study.

7.5 Summary

LCA can be effectively used to improve LEED reused, recycled and regional product criteria such that they better promote a consistent reduction of environmental burdens. However, there are several deficiencies which hinder the full incorporation of LCA into LEED. These deficiencies include inadequate public LCI data, the lack of a standardized LCI methodology, inadequate reporting transparency and inadequate correlation between building product quantities and cost. Due to these deficiencies, LCA can only be used at present to determine what building products are associated with the highest environmental burdens and thus require their own LEED criteria. Provided these deficiencies are rectified in the future, then LCA can be directly incorporated into LEED to design environmental burden-based criteria that ensure a consistent reduction of environmental burdens.

8 RECOMMENDATIONS AND CONCLUSIONS

8.1 Study Objective

The objective of this study was to illustrate the benefits and obstacles of incorporating LCA into LEED. The objective was achieved through the following study goals: assess the current state of public LCI data applicable to Canada, compare three LCI methodologies, assess the efficacy of current LEED criteria, propose modifications to LEED criteria and explore alternate environmental burden-based LEED criteria.

8.2 Summary of Study Method

The LEED-certified Medical Sciences Building (MSB) at the University of Victoria was used as a case study. Building product types, quantities and costs were collected for the structural, envelope and select interior finishings of the MSB. LCI data were then developed for the MSB using three LCI methodologies: PS-based, PMR-based and I/O-based LCI. Each LCI methodology varied in its account of upstream processes, data sources, efficiency in use and uncertainty in calculations. Various sources were used to compile LCI data for each methodology, including public LCI databases, LCA reports and national statistical reports on industry. Each LCI methodology was used to calculate the PE consumption and CO_2e emissions pertaining to the manufacture of building products in the MSB. PMR-based LCI was determined to be the most complete, convenient and consistent methodology and was selected for further use in this study.

PMR-based data were used to compare embodied to annual operational environmental burdens of the MSB and to allocate overall embodied environmental burdens to specific building products. PMR-based data were then used to assess the efficacy of LEED reused, recycled and regional product criteria in promoting reductions of PE consumption and CO_2e emissions. Based on the specific selection of reused and recycled products in the MSB, overall reductions of environmental burdens compared to the base case (i.e. no reused or recycled products) were quantified. Product selection scenarios were then modeled that maximized and minimized the reduction of environmental burdens based on a constant total value of reused and recycled products. Due to a lack of transport data, a similar assessment of regional product criteria was not conducted. Rather, building products were rated generally in terms of transport requirements per unit cost.

Based on these assessments, several modifications to the criteria were proposed and alternate environmental-burden based criteria were explored.

8.3 Key Findings

The key findings of this study are as follows:

8.2.1 State of Public LCI Data

Insufficient availability, inconsistent reporting methodologies and inadequate reporting transparency of public LCI data applicable to Canada are obstacles in the incorporation of LCA into LEED. In particular, no LCI data applicable to Canada was found for reused or recycled products.

Further, LCA studies on buildings found within journals are, for the most part, highly deficient in transparency and difficult to interpret.

8.2.2 Comparison of LCI Methodologies and Results

Using PMR-based LCI, overall environmental burdens for the MSB are 18,201 GJ PE consumption and 1,297 tonnes CO_2e emissions. PS-based results were 4.0% and 1.4% less than PMR-based results for PE consumption and CO_2e emissions, respectively. I/O-based results were 20.5% and 46.6% greater than PMR-based results for PE consumption and CO_2e emissions, respectively.

PS-based LCI underestimates environmental burdens and is inconvenient for large product systems such as a building. I/O-based LCI estimates environmental burdens with a high degree of uncertainty. PMR-based LCI, on the other hand, estimates environmental burdens within a complete, convenient and consistent mathematical framework. PMR-based LCI is thus the most suitable methodology for an LCA study and was used for further analysis in this study.

Per unit floor area, PMR-based environmental burdens are 4.45 GJ PE/m^2 and 317 kg CO_2e/m^2. These results compare well with those found in other studies. Embodied to annual operational PE consumption and CO_2e ratios are 1.86 and 5.20, respectively. The former ratio is low compared to other studies. The latter ratio compares well. The structure, envelope, and interior finishings account for

49.6%, 42.6% and 7.8% of overall PE consumption, respectively, and 67.6%, 27.7% and 4.8% of CO_2e emissions, respectively.

8.2.3 Efficacy of LEED Criteria

LEED reused, recycled and regional product criteria do not account for the large range in environmental performance of different products. As such, LEED criteria do not promote a consistent reduction of environmental burdens. Given constant reused and recycled product values that are sufficient to meet each criterion, the possible selection of products allows an impermissible range of overall reductions of environmental burdens: 1.0% to 26.2% for PE consumption and 0.5% to 25.2% for CO_2e emissions. Mass per unit cost of product varied between 7 and 14,092 kg/$1000. A similarly large range in transport energy per unit cost of product thus results. Adherence to these criteria, then, may result in a nearly negligible reduction of environmental burdens.

8.3 Recommendations

8.3.1 State of Public LCI Data

The quality and quantity of LCI data applicable to Canada must improve. The costs of conducting an LCA, however, are often prohibitively high. Thus, improvements to LCI data will require an unprecedented coalition between industry, government and non-government organizations. Given proper funding and a commitment to comprehensive and transparent data development, a public LCI database applicable to the majority of Canadian products seems attainable in the near future.

At present, reporting transparency is poor for LCA studies on buildings. Thus, ISO 14040 should stipulate the reporting requirements for an LCA study that is condensed for journal publication.

8.3.2 LCI Methodologies

PMR-based LCI should become the ISO 14040 standardized methodology for use in all future LCA studies.

8.3.3 Correlation between Building Product Quantity and Cost

To facilitate an accurate correlation between building product quantities and costs, a summary document listing both quantity and cost of each building product should be a mandatory requirement for LEED certification.

8.3.4 Modifications to LEED Criteria

Additional criteria for reused, recycled and regional products should apply to those products with the highest environmental burdens per unit cost, as listed in Table 7.1.

8.3.5 Environmental Burden-based Criteria

Provided a comprehensive and transparent LCI database is developed, then environmental burden-based criteria should replace current product-based criteria. Optimization capability within LCA-based software will greatly simplify the certification process by automatically determining the optimal combination of reused, recycled and regional products such that the criteria are met. Further research, however, is required to determine the relative life spans and costs of reused and recycled products relative to virgin products.

8.4 Final Thoughts

Since the 1970s, increased environmental awareness towards building operation and construction has led to increased efforts to improve the environmental performance of buildings. This relationship must continue into the future. Decades of work by various individuals and organizations to first identify the environmental burdens associated with buildings and then promote reductions of those burdens have collimated into the current LEED rating system. LEED has been enormously successful in creating market demand for the improved environmental performance of buildings and is by far the most established building rating system. The purpose of LEED must now move beyond a rating system merely used for market transformation to one used for a comprehensive assessment of environmental performance. At present, LEED is no such rating system. Its failure to ensure a consistent reduction of environmental burdens must be rectified in the near future.

LCA is a promising tool for such rectification. In an age of increasing environmental degradation and decreasing resource availability, the accurate measurement of environmental burdens must precede their management. LCA can only quantify environmental burdens, yet its results are critical in the informed development of policies, regulations and standards meant to improve the environmental performance of manufactured products. Though its efficacy in improving LEED criteria was specifically emphasized in the study, LCA is equally applicable across all sectors of the economy. Its ability to quantify the environmental burdens for all mass and energy flows within a system in a consistent and complete manner will become increasingly important in the redesign of our industrial society.

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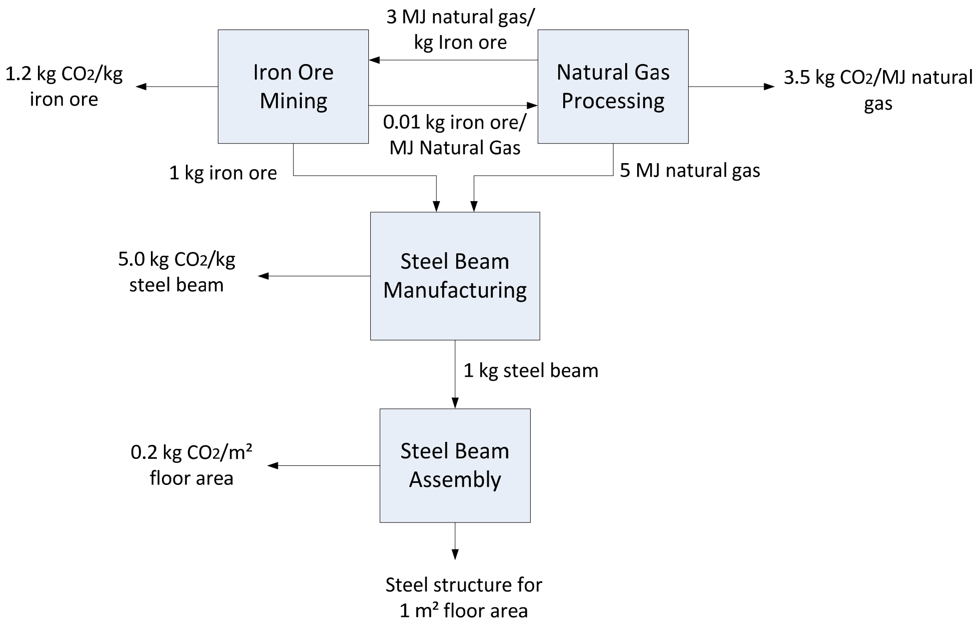
Appendix A

Application of PMR-based LCI

Consider again the following flow diagram for structural steel use in building construction:



The mass and energy flows between unit processes are summarized in Table A1.

Table A1: Modified Structural Steel Product System with Product Loop

Product	Unit Process			
	Mining of 1 kg Iron Ore	Processing of 1 MJ Natural Gas	Manufacturing of 1 kg Steel Beam	Assembly of 1 m^2 floor area
Iron Ore (kg)	1	-0.01	-1	0
Natural Gas (MJ)	-3	1	-5	0
Steel Beam (kg)	0	0	1	-1
Floor area built (m^2)	0	0	0	1

Accordingly, the product system matrix as:

$$A = \begin{bmatrix} 1 & -0.01 & -1 & 0 \\ -3 & 1 & -5 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

The CO_2e emission factors for each unit process are listed in Table A2:

Table A2: CO_2e Emissions Factors for Steel Beam Product System

Environmental Burden	**Unit Process**			
	Mining of 1 kg Iron Ore	**Processing of 1 MJ Natural Gas**	**Manufacturing of 1 kg Steel Beam**	**Assembly of 1 m^2 floor area**
CO_2e emitted (kg)	1.2	3.5	5.0	0.2

Accordingly, the environmental burden matrix is defined as:

$$B = \begin{bmatrix} 1.2 & 3.5 & 5.0 & 0.2 \end{bmatrix} \qquad (4)$$

Suppose sufficient structural steel for 1 m^2 is required. Then the total output from each unit process is calculated as follows:

$$x = A^{-1}y = \begin{bmatrix} 1 & -0.01 & -1 & 0 \\ -3 & 1 & -5 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1.083 \\ 8.247 \\ 1 \\ 1 \end{bmatrix}$$

$$E = Bx = \begin{bmatrix} 1.2 & 3.5 & 5.0 & 0.2 \end{bmatrix} \begin{bmatrix} 1.083 \\ 8.247 \\ 1 \\ 1 \end{bmatrix} = 35.4$$

Table A3: Product Requirements and Environmental Burdens for Steel Beam Product System

Product Requirements	**Environmental Burdens**
1.082 kg iron ore 8.247 MJ natural gas 1 kg structural steel	35.4 kg CO_2e emitted

Application of I/O-based LCI

Consider a simplified economy shown in Table A4 which models the steel beam product system previously described. The first four rows and columns describe the output from and input to a particular industry, respectfully. The final two columns list the value of products delivered to the final consumer and the total output from each industry. Output from a particular industry is either used as input to the same industry, used as input to a different industry, or delivered to the consumer. In Table A4, for example, the metal ore mining industry consumes $4 million of its output internally, outputs $6 million to the oil and gas industry, $80 million to the primary metal industry, $10 million to the fabricated metal product industry and delivers $22 million to the consumer for a total output of $122 million.

Table A4: Monetary Inputs and Outputs of a Simplified Economy, $ million

From	**To:**					**Total Output**
	Metal Ore Mining	**Oil and Gas Extraction**	**Primary Metal Manufacture**	**Fabricated Metal Product Manufacture**	**Consumer**	
Metal Ore Mining	4	6	80	10	22	122
Oil and Gas Extraction	47	20	35	56	305	463
Primary Metal Manufacture	4	7	11	30	95	147
Fabricated Metal Product Manufacture	20	33	10	9	84	156

The entries in Table A4 are modified in Table A5 such the monetary input from industry *i* needed to produce one unit of monetary output in industry *j* is shown. This modification is shown in Table A5. For example, the metal ore mining industry outputs $6 million to the oil and gas extraction industry which outputs a total of $463 million, as shown in Table A4. Therefore, the input from metal ore mining needed to produce one unit of monetary output from oil and gas extraction is $6 million/$463 million = 0.013. This amount is then entered appropriately in Table A5.

Table A5: Input-Output Table for Simplified Economy

From	**To**			
	Metal Ore Mining	**Oil and Gas Extraction**	**Primary Metal Manufacturing**	**Fabricated Metal Product Manufacturing**
Metal Ore	0.033	0.013	0.544	0.064

Mining				
Oil and Gas Extraction	0.385	0.043	0.238	0.359
Primary Metal Manufacturing	0.033	0.015	0.075	0.192
Fabricated Metal Product Manufacturing	0.164	0.071	0.068	0.058

Accordingly, the industry-product matrix is defined as follows:

$$C = \begin{bmatrix} 0.033 & 0.013 & 0.544 & 0.064 \\ 0.385 & 0.043 & 0.238 & 0.359 \\ 0.033 & 0.015 & 0.075 & 0.192 \\ 0.164 & 0.071 & 0.068 & 0.058 \end{bmatrix} \quad (6)$$

The CO_2e emissions and primary energy consumption related to the output of each industry are listed in Table A6:

Table A6: Environmental Burdens related to Modified Structural Steel Product System

Environmental Burden	**Environmental Burden per dollar output from industry**			
	Metal Ore Mining	**Oil and Gas Extraction**	**Primary Metal Manufacturing**	**Fabricated Metal Product Manufacturing**
CO2e emissions (kg)	1.2	3.5	5.0	0.2
Primary energy consumption (MJ)	6.4	10.8	16.0	1.1

Accordingly, the environmental burden matrix is defined as:

$$D = \begin{bmatrix} 1.2 & 3.5 & 5.0 & 0.2 \\ 6.4 & 10.8 & 16.0 & 1.1 \end{bmatrix} \quad (4)$$

Suppose that \$100 from the oil and gas industry and \$200 from the fabricated metal product manufacturing industry are required. Then the total monetary output and total environmental burdens are calculated as follows:

$$s=(I-C)^{-1}t=\left(\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}-\begin{bmatrix}0.033&0.013&0.544&0.064\\0.385&0.043&0.238&0.359\\0.033&0.015&0.075&0.192\\0.164&0.071&0.068&0.058\end{bmatrix}\right)^{-1}\begin{bmatrix}0\\100\\0\\200\end{bmatrix}=\begin{bmatrix}50.55\\229.68\\55.85\\242.46\end{bmatrix}$$

$$F=Ds=\begin{bmatrix}1.2&3.5&5.0&0.2\\6.4&10.8&16&1.1\end{bmatrix}\begin{bmatrix}50.55\\229.68\\55.85\\242.46\end{bmatrix}=\begin{bmatrix}1{,}192\\3{,}965\end{bmatrix}$$

Table A7: Total Output and Environmental Burdens for $100 Oil and Gas and $200 Fabricated Metal Output

Industry Output	Environmental Burdens
$50.55 metal ore $229.68 oil and gas $55.85 primary metal $242.46 fabricated metal	1,192 kg CO_2e emitted 3,965 MJ energy consumed

Possible Unit Processes in a Building Life Cycle

Table A8 lists both common and uncommon unit processes considered within each life cycle stage of a building.

Table A8: Life cycle stages of a building and typical processes included

Life Stage	Process
Extraction	Common • Fuel consumed by extraction equipment Uncommon • Fuel and electricity consumed by camp and administration facilities for heating, lighting, cooking • Fuel and materials used in the maintenance of machinery • Preparation of construction site and construction of facilities
Transport to Production Facility	Common • Fuel consumed by transport vehicle Uncommon • Maintenance of transport fleet • Fabrication of transport fleet
Product Manufacture	Common • Direct manufacturing processes

	Uncommon • Heating, lighting, and electrical loads of entire facility • Construction and maintenance of facility
Transport to Construction Site	• See 'Transport to Production Facility'
Construction	Common • Structural, envelope, and HVAC assembly – electricity and fuel consumed • Transportation of equipment to site Uncommon • Site planning and assessments • Site clearing • Site preparations (fences, signage, etc.) • Interior finishing • Infrastructural changes (roads, sidewalks, etc.) • Worker transportation • Maintenance of equipment
Operation	Common • HVAC and electrical loads • Water supply and heating Uncommon • Employee transport • Delivery vehicles • Wastewater treatment
Maintenance	Common • Embodied energy of material replacements in renovation and repair Uncommon • Electricity and fuel consumed by equipment during maintenance operations • Fuel consumed in maintenance crew transport
Demolition	Common • Fuel consumed by demolition equipment Uncommon • Fuel consumed in worker transport
Disposal	• See 'Transport to Production Facility'
Recycling	Common • Fuel and electricity consumed in direct recycling processes • Embodied energy credit put towards original construction material

	Uncommon • Construction and maintenance of facility • Heating, lighting, and electrical loads of entire facility

Literature Review of Adherence to ISO 14040 Criteria

Table A9 summarizes the extent to which LCA literature on buildings adhere to ISO 14040 guidelines and requirements

Table A9: Literature Review of Adherence to ISO 14040 Criteria

	Life cycle stages included	**Processes in life cycle stages**	**Data Source referenced**	**Details on data quality referenced**	**Primary energy stated**	**HHV or LHV indicated**	**Statement of Functional Unit**	**LCI Methodology Defined**
Adalberth, 1997	Yes	Yes	Yes	No	N/A	No	N/A	N/A
Blanchard and Reppe, 1998	Yes	No	Yes	To some degree	No	No	Yes	No
Borjesson and Gustavsson, 2000	Yes	No	Yes	To some degree	N/A	No	No	No
Cole, 1998	Yes	Yes	Yes	To some degree	Yes	No	No	N/A
Cole and Kernan, 1996	Yes	No	No	No	Yes	No	No	No
Dong et al, 2005	Yes	No	Yes	No	No	No	No	No
Fay et al, 2000	Yes	No	No	No	Yes	No	No	Yes
Geralli et al, 2007	Yes	No	Yes	No	No	No	Yes	Yes
Gonzales and Navarro, 2006	No	No	Yes	No	N/A	N/A	No	No
Gustavsson and Sathre, 2006	Yes	No	Yes	To some degree	Yes	No	No	No
Hacker et al, in press	No	No	Yes	No	No	N/A	No	No
Li, 2006	To some degree	No	Yes	No	No	No	No	No

	Life cycle stages included	**Processes in life cycle stages**	**Data Source referenced**	**Details on data quality referenced**	**Primary energy stated**	**HHV or LHV indicated**	**Statement of Functional Unit**	**LCI Methodology Defined**
Mithraratne and Vale, 2004	No	No	Yes	No	No	No	No	No
Scheuer et al, 2003	Yes	Yes	Yes	To some degree	Yes	Yes	No	No
Sinivuori and Saari, 2006	Yes	No	Yes	No	No	No	Yes	No
Suzuki and Oka, 1998	No	No	Yes	No	No	No	No	Yes
Thormark, 2002	Yes	No	No	To some degree	No	Yes	No	No
Thormark, 2006	Yes	No	No	To some degree	No	Yes	No	No
Yohanis and Norton, 2000	Yes	No	Yes	To some degree	Yes	No	No	Yes
Zhang et al, 2006	To some degree	No	Yes	No	No	No	No	No

Appendix B

Table B1 lists energy efficiency initiatives in Canada and BC. Table B2 lists several environmental burdens attributable to buildings.

Table B1: Energy efficiency initiatives in Canada and BC

ENERGY STAR	Eco-label for energy-efficient household appliances and equipment (OEE, 2007)
R-2000	Eco-label for energy-efficient residential buildings (OEE, 2007)
EnerGuide	Eco-label for energy-efficient home appliances and HVAC equipment (OEE, 2007)
ecoEnergy retrofit	Grants and incentives provided to residential, commercial, or institutional buildings to implement energy reduction projects (OEE, 2007)
Model National Energy Code for Buildings	A Canadian standard for energy-efficiency in buildings (OEE, 2007)
Canada Green Building Council	An organization that promotes the design and construction of sustainable buildings (CaGBC, 2003)
BC Housing Audits and Retrofits	Program to identify and improve energy efficiency in public and non-profit housing (MEMPR, 2005)
BC Hydro Power Smart	Information and incentives for energy efficiency in residential, commercial and industrial buildings (MEMPR, 2005)
Canada Mortgage and Housing Corporation refund	Refund on loan insurance for energy-efficient buildings and retrofit assistance for low-income households (MEMPR, 2005)

Table B2: Environmental Burdens of Buildings and Related Eco-Label Criteria

Environmental Burden	**Related Criteria**
Impact on local ecosystem	Preserve animal habitats Avoid ecologically sensitive zones and prime farmland Reclaim contaminated sites when possible Establish green zones and open spaces within built environment Integrate storm water flows with natural water hydrology Incorporate water conservation technologies
Air pollution	Reduce airborne dust particles during construction Reduce toxic emissions
Traffic congestion and gasoline usage	Link buildings to existing public transportation infrastructure Encourage use of alternative modes of transportation (biking) Incorporate regional materials into building construction Provide parking incentives for car pooling
Poor Indoor air quality	Reduce use of volatile organic compound-emitting building materials and finishes Provide adequate ventilation and moisture control to prevent mould growth Implement natural ventilation when feasible
Human discomfort	Increase natural light in building Implement natural ventilation when feasible Allow individual heat metering Provide open spaces within built environment Provide adequate moisture control
Resource consumption and waste streams	Reduce construction and building operational waste Incorporate recycled and reused building materials Increase the life span of buildings Implement recycling and compost programs within building
Energy usage	Calibrate and automate HVAC systems Use building simulation software during design phase Improve thermal performance of building materials Improve HVAC system efficiency Generate electricity on-site using renewable resources

Source: BRE, 2006; USGBC, 2005; iiSBE, 2007

Appendix C

Table C1 lists environmental performance categories and related point allocation for each building rating system used in Canada.

Table C1: Performance Categories and Point Allocation for Rating Systems in Canada

Green Globes		**SBTool**		**LEED**	
Category	**Points**	**Category**	**Points**[1]	**Category**	**Points**
Project Management	50	Site Selection, Project Planning and Development	9	Sustainable Sites	14
Site	115	Energy and Resource Consumption	17	Energy and Atmosphere	17
Energy	380	Environmental Loadings	20	Materials and Resources	13
Water	85	Indoor Environmental Quality	18	Indoor Air Quality (IAQ)	15
Resources	100	Service Quality	17	Water Efficiency	5
Emissions, Effluents and Other Impacts	70	Social and Economic aspects	6	Innovation and Design Process	5
Indoor Environment	200	Cultural and Perceptual Aspects	3		

Source: ECD, 2004; iiSBE, 2007; USGBC, 2005

[1] - suggested values

Appendix D

The following fuel combustion CO_2e emission factors are taken from Environment Canada's *National Inventory Report, 1990-2005: Greenhouse Gas Sources and Sinks in Canada* (Environment Canada, 2007) and are applied where applicable throughout this study.

Table D1: CO_2e Emission Factors

Combustion Fuel	**Greenhouse Gas Emissions**			
	$C0_2$ (g)	**CH_4 (g)**	**N_20 (g)**	**CO_2e (kg)**
Bituminous Coal - Electricity Generation (/kg)	2249	0.022	0.032	2.259
Bituminous Coal - Industrial Consumption (/kg)	2249	0.03	0.02	2.255
Coal Coke (/kg)	2480	0.03	0.02	2.486
Coke Oven Gas (/m^3)	1600	0.037	0.035	1.611
Diesel - General Use (/L)	2730	0.133	0.4	2.856
Diesel - Heavy Duty Truck, Uncontrolled (/L)	2730	0.15	0.075	2.756
Diesel Ships (/L)	2730	0.15	1.1	3.074
Diesel Train (/L)	2730	0.15	1.1	3.074
Gasoline - Heavy Duty Truck, Uncontrolled (/L)	2360	0.49	0.084	2.396
Gasoline Ships (/L)	2360	1.3	0.066	2.407
Kerosene - Industrial Consumption (/L)	2550	0.006	0.031	2.559
Light Fuel Oil - Industrial Consumption (/L)	2830	0.006	0.031	2.839
Lignite Coal - Industrial Consumption (/kg)	1476	0.03	0.02	1.482
Lignite Coal -Electricity Generation (/kg)	1476	0.022	0.032	1.486
Natural Gas - Electricity Generation (/m^3)	1891	0.49	0.049	1.916
Natural Gas - Industrial Consumption (/m^3)	1891	0.037	0.033	1.902
Natural Gas - Manufacturing Consumption (/m^3)	1891	0.037	0.033	1.902
Natural Gas - Pipeline Transport (/m^3)	1891	1.9	0.05	1.946
Natural Gas - Producer Consumption (/m^3)	2389	6.5	0.06	2.544
Petroleum Coke (/L)	3826	0.12	0.027	3.836
Propane (/L)	1510	0.024	0.108	1.543
Residual Fuel Oil - Electricity Generation (/L)	3080	0.034	0.064	3.100
Residual Fuel Oil - Industrial Consumption (/L)	3080	0.12	0.064	3.102
Residual Fuel Oil Ships (/L)	3080	0.28	0.079	3.110
Spent Pulping Liquor (/kg)	1428	0.05	0.02	1.435
Still Gas (/m3)	1750		2	2.370
Sub-bituminous Coal - Electricity Generation (/kg)	1733	0.022	0.032	1.743
Wood Waste - Industrial Consumption (/kg)	950	0.05	0.02	0.957

Source: Environment Canada, 2007

Appendix E

Building Product and Assembly Quantity Development

This section first lists building product and assembly quantities taken from the pre-tender estimate, as well as any assumptions and estimations used to develop the data.

Table E1: Medical Sciences Building Product and Assembly Quantity Summary

Pre-tender Estimate Data			**Products and Assemblies**		
Foundation					
Concrete in column bases, pads	360	m3	Concrete	737	m3
Concrete in grade beams	5	m3	Steel Rebar	58.313	tonnes
Concrete in Strip Footings	372	m3	Sand and Gravel	46.4	m3
Steel Rebar	58.313	tonnes			
Backfill (Sand and Gravel)	46.4	m3			

Floor Construction					
Ground Floor	1456	m2	Concrete	182	m3
- Concrete Slab, 125mm			Polyethylene vapour barrier - 6 mil	1456	m2
- 6 mm moisture barrier			Steel Rebar	45.08	tonnes
- Reinforcement					
150 mm structural fill	218	m3	Sand and Gravel	486	m3
Other imported fill	268	m3			
Upper Floors Construction	2547	m2	Concrete	610	m3
- Concrete Slab and Beams	553	m3			
- Reinforcement in slabs and beams	70.041	tonnes	Steel Rebar	77.196	
- Concrete in Columns	57	m3			
- Reinforcement in columns	7.155	tonnes			
Roof	1532	m2			
- Concrete in slabs and Beams	287	m3	Concrete	329	m3
- Reinforcement in slabs and beams	36.333	tonnes			
- Concrete in column	42	m3	Steel Rebar	41.637	tonnes
- Reinforcement to column	5.304	tonnes			
Lecture Theatre Roof					
Structural Steelwork to roof	12.693	tonnes	Galvanized Studs	13.476	tonnes
Structural Steelwork to stairs	0.783	tonnes			

Wall Construction					
Structural Walls below Main floor	385	m2	Concrete	117	m3

Concrete in walls	117	m3	Steel Rebar	14.796	tonnes
Reinforcement	14.796	tonnes	Polystyrene insulation	19.2	m3
Styrofoam Insulation (50mm)	384	m2			
Structural Walls above main floor	1371	m2	Concrete	258	m3
Concrete in walls	258	m3	Steel Rebar	32.585	tonnes
Reinforcement in walls	32.585	tonnes			
Walls above main floor	1474	m2			
Wall Type 1	657	m2	Clay brick	65.7	m3
- Brick veneer (100mm)			Polystyrene insulation	49.275	m3
- 75mm rigid insulation			Galvanized studs	1.5217	tonnes
- 92 steel stud			Screws, nuts and bolts	0.0132	tonnes
- 16mm GWB			Polyethylene vapour barrier	657	m2
- Vapour barrier			Gypsum wallboard - 16mm	657	m2
Wall Type 2 (on concrete)	372	m2	Clay brick	37.2	m3
- Brick veneer			Polystyrene insulation	27.9	m3
- 75mm rigid insulation			Polyethylene vapour barrier - 6 mil	372	m2
- Vapour barrier					
Wall Type 3					
- Kawneer 1600 Curtain Wall	301	m2	Screws, nuts, and bolts	0.1302	tonnes
			Window	301	m2
			EPDM rubber	214.94	kg
Wall Type 4					
- Kawneer 1602 window, double glazed, aluminum trim	316	m2	Window	316	m2

Exterior Doors and Screens					
Metal door and frame with glazing lights	4	paired	Window	16.304	m2
	1	single	Galvanized Sheet	0.0238	m3
Aluminum glazed door	6	paired	Aluminum	0.0413	m3
	2	single			

Roof Coverings	1529	m2			
Roof Type 1	407	m2	SBS roofing membrane	1529	m2
- 2 ply SBS membrane			Fiberglass insulation	0.98	m3
- 2 layers overlay board			Asphalt	1.0175	m3
- 75 rigid insulation			Polystyrene insulation	36.75	m3
- 6mm vapour barrier			Polyethylene vapour barrier - 6 mil	407	m2
- 13mm GWB			Gypsum wallboard -	407	m2

			16mm		
			Sand and Gravel	65.457	m3
Roof Type 2	83	m2	Polypropylene	0.8260	m3
- 2 ply SBS membrane					
- 2 layers overlay board					
- 75 rigid insulation					
- 6mm vapour barrier					
Roof Type 3	1039	m2			
- 63mm gravel					
- 2 ply SBS					
- Geotex fabric					
Parapet					
- 700mm high brick	156	m	Clay brick	30.24	m3
- 1,200mm high brick	133	m			
- 1,600mm high brick	21	m			
Roof scupper					
Cement Paving - 600x600	65	m2	Concrete	39	m3
Projections					
- 200mm concrete retaining wall	57	m2	Concrete	19.65	m3
- Concrete Slab on grade (125mm)	48	m2			
- Concrete ramp on grade (125mm)	18	m2			

Cunningham Link					
Concrete in column, bases	9	m3	Concrete	35	
Reinforcement in column	1.14	tonnes	Steel rebar	4.006	tonnes
Backfill (200mm)	3	m3	Galvanized stud	1.723	tonnes
Concrete in slab	23	m3			
Reinforcement in slab	2.866	tonnes			
Kawneer 1600 Curtain Wall	137	m2	Screws, nuts, and bolts	0.0592	tonnes
Structural steelwork	1.723	tonnes	Window	137	m2
Roof	57	m2	EPDM rubber	97.757	kg
- 2 ply SBS membrane					
- 2 layers overlay board			SBS roofing membrane	57	m2
- 75mm insulation			Fiberglass insulation	0.114	m3
- Vapour barrier			Asphalt	0.1425	m3
- 13mm GWB			Polystyrene insulation	4.275	m3
Parapet - Brick (200mm high)	48	m	Polyethylene vapour barrier - 6 mil	57	m2
Acoustic Tile	57	m2	Gypsum wallboard - 16mm	57	m2
Metal door	2	paired	Clay Brick	0.96	m3
			Gypsum wallboard - 16mm	57	m2
			Window	3.1354	m2

			Galvanized sheet	0.0062	m3

Student Lounge Patio					
Concrete slab, 125mm	160	m2	Concrete	31.652	m3
Concrete sunscreen, 605mmX150mm	86	m			
Concrete sunscreen, 450mmX150mm	57	m			

Rooftop sundries and canopies					
Structural steelwork	7.87	tonnes	Galvanized studs	10.501	tonnes
	1.68	tonnes	SBS roofing membrane	43	m2
Roof	43	m2	Gypsum wallboard - 16mm	43	m2
- SBS Membrane					
- 13mm GWB					
Structural steelwork	0.95	tonnes			

Partitions					
Fixed Partitions					
- 92 steel studs	4384	m2	Screws, nuts, and bolts	0.9027	tonnes
- 152 steel studs	865	m2	Galvanized studs	13.866	tonnes
- 16mm GWB	9145	m2	Screws, nuts, and bolts	0.1782	tonnes
- Batt insulation (25mm)	1408	m2	Galvanized studs	3.7427	tonnes
- Concrete (90mm)	110	m2	Gypsum wallboard - 16mm	9145	m2
- Concrete (100mm)	142	m2	Fiberglass insulation	35.2	m3
- Concrete (200mm)	37	m2	Concrete	31.5	m3
- Vapour barrier	833	m2	Polyethylene vapour barrier - 6 mil	833	m2
Structural Partitions					
Concrete in walls	208	m3	Concrete	208	m3
Reinforcement in walls	26.2	tonnes	Steel rebar	26.296	tonnes

Internal Doors					
Metal door, no glazing	53	units	Window		
Wood door, no glazing	44	units	- metal door	6.9392	m2
Metal door, glazing			- wood door	7.0416	m2
- 235mmX812mm	5	units	Galvanized sheet	0.8613	m3
- 275mmX1734mm	10	units	Plywood	6.5498	m3
- 275mmX1106mm	4	units			
Wood door, glazing					
- 275x812mm	22	units			
- 275x1106mm	7	units			

Finishes					
Floor Finishes					

Linoleum	2053	m2
Paint	140	m2
Vinyl flooring	63	m2
Nylon carpet	465	m2
Ceramic	111	m2
50mm styrofoam insulation	140	m2
Ceiling Finishes		
Paint	309	m2
Acoustic tile	2520	m2
GWB	200	m2
Paint	200	m2
Wood panel	497	m2
Steel stud framing	239	m2
GWB framing	110	m2
Wall Finishes		
Paint	10,555	m2
Ceramic Tile	356	m2
Acoustic tile	468	m2
Wood paneling	35	m2

Linoleum Flooring	2053	m2
Vinyl flooring	63	m2
Nylon carpet	465	m2
Ceramic tile	467	m2
Polystyrene insulation	7	m3
Latex Paint	11,204	m2
Gypsum wallboard - 16mm	3298	m2
Plywood	6.916	m3
Screws, nuts, and bolts	0.008	tonnes
Galvanized studs	0.568	tonnes

Assumptions and estimations used to develop the data include the following:

Structural Assembly

- All concrete is assumed to be 30 MPa
- Stud spacing assumed to be 400mm
- 64 and 102 gauge studs assumed to be 92 gauge
- 200mm thick backfill assumed in foundation

Envelope Assembly

- Door dimensions are assumed to be 2.286m x 91.44m x 0.045m
- Steel and aluminum doors consist of 6mm metal by thickness, remainder is air space
- Exterior doors are 75% glazing by area
- Interior doors are 10% glazing by area
- Overlay board assumed to consist of 2 x 1mm thick fiberglass outer layers (modeled as fiberglass insulation) and 2.5mm thick inner layer of asphalt

- ‘Geotex’ Fabric thickness is assumed to be 0.795mm and is made of polypropylene (Source: http://www.geo-tex.co.uk/geo-tex%20products.htm)

Additional Notes

Athena Impact Estimator used in the quantification of the following materials

- Screws, nuts and bolts (used in steel stud assembly)
- Nails (used in gypsum wallboard)
- Galvanized studs (used is steel stud assembly)
- EPDM rubber (used in curtain wall assembly
- Aluminum trim along windows (used in curtain wall assembly and window assembly)

The following table lists unit conversion factors for various building products for application in LCI data.

Table E2: Unit Conversion Factors for Medical Sciences Building Products and Assemblies

Material	**Conversion Factor**	**Source**
Aluminum	2700 kg/m3	http://www.simetric.co.uk/si_metals.htm
Asphalt	1030 kg/m3	NREL, 2005
Clay brick	1,436 kg /m3	Venta, 1998
Fiberglass insulation	25 kg/m3	Norris, 1999
Latex Paint	2.31 kg/m2 of wall	Norris, 1999
Plywood	436.6 kg/m3	NREL, 2005
Polyethylene vapour barrier	0.143 kg/m2	Norris, 1999
Polypropylene	855 kg/m3	NREL, 2005
Polystyrene insulation	42.5 kg/m3	Norris, 1999
Sand and gravel	1,650 kg/m3	http://www.simetric.co.uk/si_materials.htm
SBS roofing membrane	3.97 kg/m2	Franklin Associates, 2001

I/O-based Data Development

Table E3 lists data taken from the Medical Sciences Building LEED submission document (TBKG, 2004). Each building product is correlated to a specific NAICS L-level industry.

Table E3: Medical Sciences Building Product and Assembly Cost Summary and Industry Allocation

Building Product	**Value ($)**	**Industry Allocation**
Road base and sand	70,000	Non-metallic Mineral Mining
Concrete	350,000	Non-metal Mineral Product Manufacturing
Flyash	40,000	Non-metal Mineral Product Manufacturing
Pre-cast concrete	35,000	Non-metal Mineral Product Manufacturing
Concrete block	8,480	Non-metal Mineral Product Manufacturing
Clay brick	115,000	Non-metal Mineral Product Manufacturing
Structural steel	45,800	Fabricated Metal Manufacturing
Blueskin weather barrier	12,276	Plastic Product Manufacturing
Spray insulation	25,920	Plastic Product Manufacturing
Type x GWB	3,950	Non-metal Mineral Product Manufacturing
ISO insulation	12,750	Plastic Product Manufacturing
Vapour barrier	4,845	Plastic Product Manufacturing
Roof membrane	10,050	Petroleum and Coal Product Manufacturing
Type N insulation	15,829	Plastic Product Manufacturing
Roofing membrane primer	18,280	Petroleum and Coal Product Manufacturing
Hollow metal doors	33,000	Fabricated Metal Manufacturing
Wood doors	22,028	Wood Product Manufacturing
Spandrel glass	10,000	Non-metal Mineral Product Manufacturing
Sealed units	98,000	Non-metal Mineral Product Manufacturing
Aluminum extrusions	114,000	Fabricated Metal Manufacturing
Steel studs	52,338	Fabricated Metal Manufacturing
GWB	61,200	Non-metal Mineral Product Manufacturing
Ceramic Tile	19,240	Non-metal Mineral Product Manufacturing
Acoustic tile	25,000	Non-metal Mineral Product Manufacturing
Linoleum	75,247	Plastic Product Manufacturing
Carpet	31,500	Textile and Textile Product Mills
Latex paint	48,080	Miscellaneous Chemical Product Manufacturing
Reinforcement Steel	210,000	Fabricated Metal Manufacturing
Total	1,567,813	

Appendix F

Table F1 summarizes the unit processes modeled in the process-based LCI.

Table F1: Unit Processes Modeled in this Study

Building Products	Petroleum Products	Other Intermediate Products	Primary Energy Resources	Primary non-Energy Resources	Transportation
Aluminum	Asphalt	Caustic Soda	Bituminous Coal	Limestone	Barge
Cement	Benzene	Chlorine	Crude Oil	Bauxite Ore	Freighter
Ceramic Tile	Butadiene	Concrete Mortar	Electricity	Clay and Shale	Pipeline - Natural Gas
Clay Brick	Diesel	Flyash	Lignite Coal	Gypsum	Pipeline- Coal
Concrete	Ethylene	Glass	Natural Gas	Ilmenite Ore	Pipeline- Petroleum Products
EPDM rubber	Gasoline	Iron Pellet	Sub-bituminous Coal	Iron Ore	Rail
Fiberglass Insulation	Kerosene	Lime	Uranium Oxide	Jute	Truck
Gypsum Board	Light Fuel Oil	Nitrogen		Linseed Oil	
Latex Paint (kg)	Petroleum Coke	Oxygen		Mica	
Linoleum Flooring	Propane	Polyethylene		Salt	
Nylon Carpet	Propylene	Polypropylene		Sand and Gravel	
Plywood	Pygas	Polyvinyl Acetate		Sandstone	
Polystyrene Insulation	Residual Fuel Oil	Polyvinyl Chloride		Softwood	
SBS roofing membrane	White Mineral Oil	Styrene Butadiene		Talc	
Steel - Galvanized Sheet		Titanium Dioxide			
Steel - Galvanized Studs					
Steel - Screws, Nuts, and Bolts					
Steel Nails					
Steel Rebar					
Vinyl Flooring					
Window Assembly					

The inputs to and CO_2e emission output from each unit process are listed below. CO_2 emissions are listed for direct fuel consumption only. CO_2 emissions pertaining to electricity consumption and transport requirements are listed in their respective unit processes. Transport requirements estimated using StatsCan data are listed in a separate table for each unit process. Transport requirements taken directly from LCI data are listed in the same table as mass and energy inputs.

Aluminum – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	15.9400	
RFO (L)	0.21559	0.66883
Diesel (L)	0.00530	0.01513
Gasoline (L)	0.00043	0.00102
Natural Gas (m3)	0.53699	1.02135
Bituminous Coal (kg)	0.01658	0.66883
Petroleum Coke (kg)	0.40368	0.01513
Asphalt (kg)	0.10303	
Bauxite (kg)	5.09520	
Caustic Soda (kg)	0.14263	
Lime (kg)	0.08820	0.24169 (Calcination)
Rail (tonne-km)	1.68031	
Freighter (tonne-km)	11.2938	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Aluminum to DC	0.19428	3.53518

Cement – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.15875	
Natural Gas (m3)	0.06064	0.11533
Bituminous Coal	0.07593	0.15784
Residual Oil (L)	0.00360	0.01116
Petroleum Coke (kg)	0.00600	0.02011
Limestone (kg)	1.17000	0.49833
Clay/Shale (kg)	0.32000	
Iron (kg)	0.03000	
Sand (kg)	0.07000	
Ash (kg)	0.01000	
Gypsum (kg)	0.09000	
Truck (tonne-km)	0.12212	
Rail (tonne-km)	0.00116	
Freighter (tonne-km)	0.68058	

Ceramic Tile – 1 m^2

	Consumption	**CO_2e Emissions (kg)**
Natural Gas (m3)	2.4629	4.6845
RFO (L)	0.20948	0.64990
Bit. Coal (kg)	0.56535	1.2753
Mortar (kg)	4.2478	
Styrene Butadiene (kg)	1.8553	
Glass (kg)	20.420	
Clay (kg)	6.8070	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Clay to plant	0.8855	0.3984
Glass to plant	11.5011	0.0000
Styrene Butadiene to plant	0.1817	2.4293
Mortar to plant	1.2749	0.7836
Ceramic Tile to dist. Centre.	8.1719	18.8716

Clay Brick – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Natural Gas (m3)	0.06687	0.12719
Diesel (L)	0.00073	0.00209
Electricity (kWh)	0.53422	
Clay (kg)	1.00000	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck
Raw materials to plant	0.02102
Clay Brick to DC	1.54000

Concrete – 1 m^3

	Consumption	**CO_2e Emissions (kg)**
Natural Gas (m3)	2.126	4.04363
Diesel (L)	3.823	10.92086
Electricity (kWh)	3.873	
Fly Ash (kg)	31.000	
Coarse Aggregate (kg)	1092.0	
Sand (kg)	722.00	
Cement (kg)	319.00	
Truck (tonne-km)	45.050	
Rail (tonne-km)	43.400	
Freighter (tonne-km)	49.600	

EPDM – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.07980	
Fuel Oil (L)	0.00146	0.00454
Diesel (L)	0.00003	0.00009
Gasoline (L)	0.00001	0.00003
Natural gas (m3)	0.02913	0.05541
LPG (L)	0.00004	0.00006
Pet. Coke (L)	0.39296	
Ethylene (kg)	0.41800	
Propylene (kg)	0.19700	
Butadiene (kg)	0.02500	
Clay (kg)	0.06000	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Clay to plant	0.007806	0.031023
EPDM to DC	0.097921	1.30934

Gypsum Board – 1 m^2

	Consumption	**CO_2e Emissions (kg)**
Natural Gas (m3)	0.91685	1.74385
Residual Oil (L)	0.21172	0.65681
Electricity(kWh)	0.93432	
Gypsum (kg)	10.0067	
Clay (kg)	0.01146	
Talc (kg)	0.02561	
Mica (kg)	0.02359	
Limestone (kg)	0.3525	
PVA Resin (kg)	0.02696	
Truck (tonne-km)	7.2812	
Rail (tonne-km)	3.6973	
Freighter (tonne-km)	28.816	

Latex Paint – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.24600	
Natural Gas (m3)	0.03607	0.06861
PVA (kg)	0.25000	
Titanium Dioxide (kg)	0.12500	
Limestone (kg)	0.12500	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Limestone to plant	0.00828	0.044603
Titanium dioxide to plant	0.036742	0.026734
PVA to plant	0.045917	0.175259
Paint to DC	0.37313	0

Linoleum Flooring – 1 m^2

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	1.6111	
Natural Gas (m3)	0.7579	1.4417
Linseed Oil (kg)	0.894	
Limestone (kg)	0.509	
Plywood (kg)	1.021	
Titanium Dioxide (kg)	0.127	
Jute (kg)	0.313	
Truck (tonne-km)	0.0635	
Rail (tonne-km)	2.3608	
Freighter (tonne-km)	7.0189	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Linoleum to DC	0.8704	2.0100

Nylon Carpet – 1 m^2

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	2.60861	
Natural Gas (m3)	1.58862	3.021572
Crude Oil (L)	0.70134	
RFO (L)	0.11765	0.364984
Bit. Coal (kg)	0.50350	1.135821
Lignite Coal (kg)	0.09445	0.140057
Polypropylene (kg)	0.22700	
Styrene Butadiene Latex (kg)	0.26300	
Limestone (kg)	0.97541	
Bauxite (kg)	0.00302	
Iron (kg)	0.00071	
Titanium Dioxide (kg)	0.00067	
Sand (kg)	0.00038	
Salt (kg)	0.05687	
Rail (tonne-km)	0.00212	
Freighter (tonne-km)	0.01705	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Polypropylene to plant	0.04169	0.15914
Styrene Butadiene to plant	0.02575	0.34436
Limestone to plant	0.06461	0.34805
Iron Ore to plant	0	0.00067
Titanium Dioxide to plant	0.00020	0.00014
Sand to plant	0.00005	0.00022
Salt to plant	0.01044	0.01856
Carpet to DC	1.08600	0

Plywood – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.264387	
Natural Gas (m3)	0.026851	0.051070
Diesel (L)	0.021576	0.061638
LPG (L)	0.002155	0.003328
Gasoline (L)	0.000066	0.000157
Coal (kg)	0.000001	0.000002
Softwood (kg)	1.100192	0.147775
Truck (tonne-km)	0.414249	
Rail (tonne-km)	0.000106	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Plywood to DC	0.164768307	0.808191

Polystyrene Insulation – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.278722	
Natural Gas (m3)	0.446313	0.84889
Ethylene (kg)	0.292707	0.260739 (Process)
Benzene (kg)	0.782217	
White Mineral Oil (kg)	0.00257	
Truck (tonne-km)	0.242769	
Rail (tonne-km)	0.329587	
Freighter (tonne-km)	0.250808	
Barge (tonne-km)	1.048249	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Polystyrene to DC	0.183666	1.30934

SBS Roofing Membrane

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	1.49179	
Residual Oil (L)	0.07598	0.23572
Natural gas (m3)	0.10207	0.19414
Limestone (kg)	0.19500	
Asphalt (kg)	0.63500	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Road	**Rail**
SBS to DC	0.09792108	1.309340046
Limestone to plant	0.012916598	0.069580973

Fiberglass Insulation – 1 m^2

	Consumption	CO_2e Emissions (kg)
Electricity (kWh)	0.27778	
Natural Gas (m3)	0.01542	0.029335
Bit. Coal (kg)	0.00585	0.013197
Limestone (kg)	0.2442	
Sand (kg)	0.20729	
Salt (kg)	0.1130	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	Rail
Limestone to plant	0.01618	0.08714
Sand to plant	0.02582	0.06879
Salt to plant	0.02075	0.03688
Insulation to DC	0.18008	0.41587

Steel Products – 1 kg

	Nails	Screws, nuts, bolts	Rod/Rebar	Galvanized sheet	Galvanized stud
Lime (kg)	0.08129	0.08779	0.07885	0.06905	0.06933
Limestone (kg)	0.06751	0.07292	0.06549	0.05735	0.05758
Iron Pellet (kg)	1.30993	1.38293	1.27229	1.03121	1.03535
Bituminous Coal (kg)	0.66467	0.70068	0.64472	0.52255	0.52464
Electricity (kWh)	1.81876	1.48220	0.46687	1.25266	0.80297
Natural Gas (m3)	0.19672	0.24529	0.12425	0.03526	0.03540
Oxygen (kg)	0.06835	0.07382	0.06630	0.05806	0.05830
Comb. Truck(tonne-km) [1]	0.01428	0.07599	0.06825	0.05931	0.06002
Rail (tonne-km) [1]	0.47036	0.48541	0.45648	0.36990	0.37138
Barge (tonne-km) [1]	4.27243	4.50975	4.14904	3.36286	3.37636
Total CO2e emissions (kg)	2.10147	2.28604	1.91364	1.58680	1.59186

[1]- Transportation of raw materials (lime, limestone, iron, and coal) to plant and steel to DC

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	Rail
Steel to DC	0.263537	1.04985

Vinyl Flooring – 1 m^2

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	2.4971	
Natural Gas (m3)	0.1468	0.279311
PVC (kg)	0.7970	
Polypropylene (kg)	0.2690	
Styrene Butadiene (kg)	0.1431	
Limestone (kg)	5.5400	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Limestone to plant	0.36696	1.97681
PVC to plant	0.14638	0.55872
Polypropylene to plant	0.04940	0.18857
Styrene Butadiene to plant	0.01401	0.18744
Vinyl flooring to DC	1.21403	8.65473

Window – 1 m^2

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	18.3611	
Bituminous Coal (kg)	0.32200	0.7263
Residual Fuel Oil (L)	0.01331	0.0412
Natural Gas (m3)	4.26299	8.1082
Limestone (kg)	10.4472	
Sandstone (kg)	14.0000	
Salt (kg)	6.20000	
Aluminum (kg)	0.04705	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Salt to plant	1.13838	2.02356
Limestone to plant	0.69201	0.35682
Sandstone to plant	0.92734	4.99555
Window to DC	14.0806	0
Aluminum to plant	0.00914	0.16633

Petroleum Products

	Asphalt – 1 kg	Benzene – 1 kg	Butadiene – 1 kg	Diesel – 1L	Ethylene – 1 kg	Gasoline – 1L	Kerosene – 1L	Light Fuel Oil – 1L	Liquid Petroleum Gases – 1L	Petroleum Coke – 1L	Propylene – 1 kg	Pygas – 1 kg	Residual Fuel Oil – 1L	White Mineral Oil – 1 kg
Electricity (kWh)	0.14308	0.12039	0.31461	0.12409	0.18530	0.10574	0.13515	0.12541	0.07757	0.16363	0.19309	0.20435	0.13515	0.55755
Natural gas (m3)	0.01111	0.04664	1.43372	0.00953	1.81244	0.00812	0.01050	0.00974	0.00596	0.01257	1.43006	1.38407	0.01038	0.08571
Diesel (L)		0.00334	0.00005		0.00008						0.00002	0.00002		0.00000
Gasoline (L)		0.00000	0.00006		0.00009						0.00002	0.00002		0.00000
RFO (L)	0.02720	0.05044	0.00868	0.02359	0.00736	0.02010	0.02570	0.02384	0.01475	0.03111	0.00846	0.00884	0.02570	0.20911
LPG (L)	0.00117	0.00078	0.00037	0.00101	0.00032	0.00086	0.00110	0.00102	0.00063	0.00134	0.00812	0.00038	0.00110	0.00893
Crude Oil (L)	1.16491	0.78688	0.37633	1.01027	0.31900	0.86090	1.11433	1.03400	0.63154	1.33218	0.36689	0.38341	1.10031	1.17972
Pygas (kg)		0.33500									0.00000	0.00000		0.00000
Pipeline Petroleum (tonne-km)		0.00000	0.14484	0.39918	0.19312	0.34016	0.37238	0.40342	0.24954	0.52638	0.06276	0.00499	0.43476	0.00000
Rail (tonne-km)	0.02800	0.00000	0.30578	0.02429	0.00000	0.02070	0.02266	0.02454	0.01518	0.03202	0.00000	0.37015	0.02645	0.88514
Truck (tonne-km)	0.04377	0.00000	0.30578	0.03796	0.00000	0.03235	0.03541	0.03837	0.02373	0.05006	0.00000	0.00000	0.04135	0.88514
Barge (tonne-km)	0.23722	0.18524	0.00000	0.20573	0.00000	0.17532	0.19192	0.20792	0.12861	0.27129	0.00000	0.00000	0.22407	0.00000
CO2e emissions (kg)	0.14275	0.21371	0.13790	0.12360	0.12446	0.10532	0.13463	0.12512	0.07726	0.16298	0.12661	0.11277	0.13461	0.82375

Other Intermediate Products

Caustic Soda – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.93846	
Natural gas (m3)	0.13192	0.25092
Bituminous Coal (kg)	0.03566	0.08695
Residual oil (L)	0.00210	0.00650
Salt (kg)	0.87439	
Pipeline- Coal (tonne-km)	0.36837	
Rail tonne-km)	0.00402	
Barge (tonne-km)	0.00402	

Chlorine – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.98988	
Natural Gas (m3)	0.12079	0.22976
RFO (L)	0.00050	0.00155
Bituminous Coal (kg)	0.0256	0.06243
Salt (kg)	0.891	
Pipeline (tonne-km)	0.01	
Truck (tonne-km)	0.08	
Rail (tonne-km)	0.21	

Glass – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.11111	
LPG (L)	0.02228	0.03440
Limestone (kg)	0.15931	
Lime (kg)	0.13091	
Sand (kg)	0.11987	
Soda (kg)	0.21451	

Estimated Transport Requirements based on StatsCan Data (tonne-km)

	Truck	**Rail**
Limestone to plant	0.010552	0.056844441
Lime to plant	0.008672	0.046713749
Sand to plant	0.014931	0.039782667
Caustic soda to plant	0.063052	0.045877642
Glass to DC	0.563225	0

Iron Pellet – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.27657	
Natural Gas (m3)	0.00105	0.00199
Light Fuel Oil (L)	0.00062	0.00177
Gasoline (L)	0.00003	0.00007
Iron Ore	1.150	

Jute – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.24698	
Natural Gas (m3)	6.56E-05	0.00012
Diesel (L)	0.23077	0.65928
LPG (L)	0.00276	0.00427
Nitrogen (kg)	0.23945	1.76635 (process)
Lime (kg)	0.15787	
Rail (tonne-km)	0.30195	
Truck (tonne-km)	0.42873	

Lime – 1 kg

	Consumption	CO_2e Emissions (kg)
Electricity (kWh)	0.06770	
Natural Gas (m3)	0.02079	0.03954
Bituminous (kg)	0.17200	0.41948
Diesel (L)	0.00094	0.00270
LPG (L)	0.00003	0.00005
Limestone (kg)	1.87500	0.76800 (Calcination)
Combination Truck (tonne-km)	0.07993	
Rail (tonne-km)	0.01599	
Barge (tonne-km)	0.02398	

Linseed Oil – 1 kg

	Consumption	CO_2e Emissions (kg)
Diesel (L)	8.61E-03	0.0246
Nitrogen (kg)	6.71E-03	0.3073 (process)
Rail (tonne-km)	3.79E-02	
Truck (tonne-km)	5.39E-02	

Nitrogen – 1 kg

	Consumption	CO_2e Emissions (kg)
Electricity (kWh)	0.0506	
Natural Gas (m3)	18.248	0.53431
Coal (kg)	0.0081	0.01827
Road (tonne-km)	0.2043	
Rail (tonne-km)	0.6196	

Oxygen – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.13801	
Pipeline (tonne-km)	0.001609	

Polyethylene – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.18850	
Natural Gas (m3)	0.03802	0.07231
Residual Oil (L)	0.00134	0.00414
LPG (L)	0.00003	0.00005
Olefin (Propylene) (kg)	1.00800	0.01005 (Process)
Truck (tonne-km)	0.18366	
Rail (tonne-km)	1.30934	

Polypropylene – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.16314	
Natural Gas (m3)	0.01935	0.03681
Residual Oil (L)	0.00434	0.01346
Olefin (Propylene) (kg)	0.99600	0.01935 (Process)

Polyvinyl Chloride – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.61596	0.1394
Natural Gas (m3)	0.18310	0.3482
Ethylene (kg)	0.45345	0.3733 (Process)
Chlorine (kg)	0.53554	
Oxygen (kg)	0.14414	
Rail (tonne-km)	0.28079	
Pipeline (tonne-km)	0.00386	

Polyvinyl Acetate – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.68353	
Natural Gas (m3)	0.25851	0.34171
Diesel (L)	0.01277	0.03647
RFO (L)	0.06413	0.19897
Bit Coal	0.01890	0.03929
Ethylene (kg)	0.19992	0.26661 (Process)
Oxygen (kg)	0.22326	
Barge (tonne-km)	0.00606	
Pipeline - Petroleum (tonne-km)	0.00082	
Pipeline – Natural Gas (tonne-km)	0.00015	
Rail (tonne-km)	0.52326	

Styrene Butadiene – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	0.76876	
Natural Gas (m3)	0.36300	0.69043
Bituminous Coal (kg)	0.06840	0.15430
RFO (L)	0.00018	0.00056
Ethylene (kg)	0.19690	0.17539 (Process)
Propylene (kg)	0.21500	
Benzene (kg)	0.52618	
Butadiene (kg)	0.14616	
Barge (tonne-km)	0.90901	
Freighter (tonne-km)	0.50780	
Truck (tonne-km)	0.10336	
Rail (tonne-km)	0.23006	

Titanium Dioxide – 1 kg

	Consumption	**CO_2e Emissions (kg)**
Electricity (kWh)	13.055	
Bituminous Coal (kg)	1.1880	2.6799
Ilmenite Ore (kg)	5.0	

Primary Energy Resources

	1 kg Uranium oxide	**1 L Crude Oil**	**1 m3 Natural Gas**	**1 kg Bituminous Coal**	**1 kg Lignite Coal**
Electricity (kWh)	3938.05	0.03288	0.04545	0.03877	0.05330
Natural Gas (m3)	229.34	0.02732	0.05027	0.00016	0.00025
Diesel (L)	13.76	0.00109	0.00102	0.00875	0.01492
RFO (L)		0.00067	0.00065	0.00083	0.00142
Gasoline (L)		0.00058	0.00056	0.00083	0.00142
Crude Oil (L)		0.00010	0.00010		
Bituminous Coal (kg)	22.73			0.00043	
Lignite Coal (kg)					0.00036
Truck (tonne-km)	19.11		0.01199	0.12638	0.01100
Freighter (tonne-km)	54.00	2.39837			
Barge (tonne-km)		0.00072		0.00688	
Pipeline - Petroleum (tonne-km)		0.40816			
Pipeline - Natural Gas (tonne-km)			1.19926		
Pipeline - Coal Slurry (tonne-km)				0.00502	
Rail (tonne-km)			0.01199	1.04192	0.00103
CO_2e emissions					
- Natural Gas	436.21	0.05196	0.12790	0.00030	0.00047
- Diesel	26.77	0.00212	0.00199	0.01704	0.02905
- RFO		0.00209	0.00201	0.00259	0.00440
- Gasoline		0.00139	0.00135	0.00200	0.00340
- Crude Oil[1]		0.00033	0.00030		
- Bituminous Coal	55.43			0.00105	
- Lignite Coal					0.00053
- Process		0.06577	0.02908	0.08384	0.02363

[1] - Emission factor for residual fuel oil combustion in industry is assumed

Electricity

Total Generation in 2005

Fuel Type	Electricity Produced (MWh)	Percentage of Electricity Generation	Fuel Consumed
Hydro	303,591,014	58.47%	
Bituminous	34,113,284	6.57%	1.466E+10 kg
Sub-bituminous	42,986,757	8.28%	2.545E+10 kg
Lignite	14,866,053	2.86%	1.122E+10 kg
Residual Fuel Oil	12,141,253	2.34%	3.112E+09 L
Natural Gas	26,259,010	5.06%	7.139E+09 m3
Uranium oxide	85,239,845	16.42%	1.553E+06 kg

Source: StatsCan, 2006d

Fuel Consumption per kWh Electricity

	Fuel Consumed per Average kWh	CO_2e Emissions per kWh (kg)
Bituminous (kg)	0.02824	0.06380
Sub-bituminous (kg)	0.04902	0.08546
Lignite (kg)	0.02161	0.03213
Residual Fuel Oil (L)	0.00599	0.01858
Natural Gas (m3)	0.01375	0.02635
Uranium (kg)	2.992E-06	0

Non-metallic Mineral Resources

Energy Consumption per kg extracted non-metallic mineral

	Limestone	Sandstone	Sand and Gravel	Shale and Refractory	Gypsum Quarrying	Salt	Talc and Mica
Electricity (kWh)	0.001698	0.001273	0.000831	0.017933	0.002591	0.013195	0.030650
Natural Gas (m3)	0.000049		0.000054	0.000082		0.002553	0.004352
Heavy Fuel Oil (L)			0.000007			0.000524	0.001490
Diesel (L)	0.000410	0.000540	0.000485	0.000532	0.001200	0.000358	0.019348
Light Fuel Oil (L)	0.000022	0.000004	0.000017	0.001024	0.000010	0.000015	
Gasoline (L)	0.000017	0.000035	0.000047	0.000027	0.000024	0.000006	
Kerosene (L)							
LPG (L)	0.000007		0.000007	0.000020	0.000008	0.000021	0.000292

CO_2e emissions per kg extracted non-metallic mineral

	Limestone	Sandstone	Sand and Gravel	Shale and Refractory	Gypsum Quarrying	Salt	Talc and Mica
Natural Gas	0.0000936		0.0001034	0.0001558		0.0048561	0.0082771
Residual Fuel Oil	0.0000010		0.0000226			0.0016262	0.0046214
Diesel	0.0011708	0.0015422	0.0013869	0.0015205	0.0034279	0.0010234	0.0552726
Light Fuel Oil	0.0000629	0.0000121	0.0000482	0.0029075	0.0000297	0.0000428	
Gasoline	0.0000412	0.0000851	0.0001127	0.0000645	0.0000577	0.0000150	
Kerosene	0.0000002						
LPG	0.0000108		0.0000108	0.0000307	0.0000126	0.0000328	0.0004510
Total	0.0017647	0.0019275	0.0018727	0.0087376	0.0041141	0.0105826	0.0755588

Metallic mineral mining

	Iron Ore		**Bauxite Ore**		**Ilmenite Ore**	
	Consumption	**CO_2e Emissions (kg)**	**Consumption**	**CO_2e Emissions (kg)**	**Consumption**	**CO_2e Emissions (kg)**
Electricity (kWh)	0.11654		0.0004		0.04421	
Natural Gas (m3)					0.00019	0.00037
Heavy Fuel Oil (L)	0.0085	0.026368	0.001228	3.809923		
Diesel (L)	0.00209	0.005982	0.00437	9.89E-04	0.00188	0.00539
Light Fuel Oil (L)	0.000058	0.000164			0.00012	0.00034
Gasoline (L)	0.00011	0.000252	0.00027	6.11E-05	0.00010	0.00025
Kerosene (L)						
LPG (L)	0.000065	0.000101			0.00312	0.00481

Transportation

	Fuel consumed per tonne-km (L)	Percentage Fuel Type			CO_2e emissions per tonne-km (kg)
		Gasoline	Diesel	Residual Oil	
Combination Truck	0.027221	0.18	0.82		0.07326
Barge - Diesel	0.009592		0.22		0.02787
- RFO	0.008814			0.78	
Freighter	0.004925	0	0.1	0.9	0.01530
Rail	0.006429		1		0.01976
Single Truck	0.015411	0.5	0.5		0.03970

	Electricity consumed per tonne-km (kWh)	Natural Gas Consumed per tonne-km (m^3)	CO_2e emissions per tonne-km (kg)
Pipeline – Natural Gas		0.01338	0.02604
Pipeline – Petroleum	0.0149		
Pipeline – Coal Slurry	0.1644		

Appendix G

Appendix G describes data development methodologies for each unit process when missing or inadequate data are encountered.

Building Products

Cement

LCI data are taken from the ASMI LCI data set (CCMET et al, 1999). Data quality is sufficient for this study.

Concrete

LCI data are taken from the ASMI LCI data set (CCMET et al, 1999). Data quality is sufficient for this study.

Clay Brick

LCI data are taken from the ASMI LCI data set (Venta, 1998). Data quality is sufficient for this study.

Gypsum Wall Board

LCI data are taken from the ASMI LCI data set (Venta, 1997). Data quality is sufficient for this study.

Window Assembly

LCI data are taken from the ASMI LCI data set (Norris, 1999). Data quality is not adequate as only the total flows between the environment and the product system are presented. The following modifications were made to make the data more suitable for use in this study

1) Athena Impact Estimator software was used to determine that each m^2 of window requires 12.9 kg of aluminum perimeter. This relation is applied throughout the study.
2) No LCI data could be found for sulphur production. Thus sulphur is excluded as an input.
3) Crude oil is listed in the data though it was indicated that residual oil is used in glass production (Norris, 1999). Crude oil is converted to residual fuel oil equivalent based on U.S LCI data for production of residual oil (NREL, 2005).
4) The term ‘gas’ is assumed to refer to natural gas

5) Dolomite and feldspar are assumed to be derived from limestone and are thus quantified as such
6) Quartzsand is assumed to be sandstone
7) All transport requirements are estimated from StatsCan (StatsCan, 2005a, StatsCan, 2005b)

Aluminum

LCI data are taken from the NREL LCI Database module for 'Primary Aluminum Production' (NREL, 2005). Data is split into two unit processes for bauxite mining and aluminum production. Inputs of 'calcinated coke' and 'green coke' in anode production are forms of petroleum coke (API, 2000) and are equated as such. LCI data on aluminum fluoride and cathode carbon could not be found. Thus, these inputs are excluded from analysis.

Styrene-Butadiene-Styrene (SBS) Roofing Membrane

LCI data is taken from the ASMI LCI data set (Franklin Associates, 2001). Data quality is not adequate as only the total flows between the environment and the product system are presented. Further, energy is expressed in LHV and electricity is not specified. In its place, NREL LCI data for acrylonitrile butadiene styrene is used (NREL, 2005). Only the unit processes within the data pertaining to the production of butadiene and styrene and their polymerization are included. These unit processes were:

- Polybutadiene production
- Ethylbenzene styrene production
- Acrylonitrile butadiene styrene polymerization

The polymerization step also includes the polymerization of acrylonitrile. The impact on results is unknown but is expected to be minor.

Transport of SBS roofing membrane to a distribution centre is estimated using StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Ethylene-Propylene Diene Monomer (EPDM) Membrane

LCI data are taken from the ASMI data set (Franklin Associates, 2001). Data has the same limitations as that for SBS roofing membrane. A flow diagram given in the report quantifies the material inputs into EPDM production. These quantities are adopted in this study and unit processes are developed for each input. The one exception is the input of ‘carbon black’, which is assumed to be equivalent to ‘carbon anode’ whose LCI data are included in the NREL LCI data module for primary aluminum production (NREL, 2005). The production of carbon anode is incorporated within the unit process for EPDM membrane production. Process energy for the polymerization of EPDM and conversion into a membrane building product is unavailable and not included in this study.

Transport of clay to the EPDM rubber plant and EPDM rubber to the distribution centre are estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Steel Products

LCI data are taken from the ASMI data set (MES, 2003). Five steel products are considered in this study:

- Steel rebar
- Galvanized studs
- Galvanized sheets
- Screws, nuts, and bolts
- Steel nails

Data quality is not adequate as only the total flows between the environment and the product system are presented. However, process flow diagrams are provided for each unit process considered within the module. These diagrams allow the subtraction of energy and material inputs related to unit processes modeled elsewhere in this study from the cumulated total. What remains is the data for the production of liquid steel and the manufacturing of the various steel products. Omitted from the steel module and included as separate unit processes are the following:

- Lime production
- Limestone extraction
- Mining, crushing, and pelletizing of iron ore
- Coal mining and processing

Specific material and energy factors subtracted from the steel LCI module include the following:

Lime Production

Electricity (MJ)	0.15972
Natural Gas (MJ)	6.4493

Limestone Extraction (per kg limestone)

Electricity (MJ)	0.02064
Gasoline (MJ)	0.0012082
Diesel (MJ)	0.0218

Mining, Crushing, Concentrating, Pelletizing of Iron Ore (per kg iron ore)

Electricity (MJ)	1.4152
Natural Gas (MJ)	0.04
Diesel (MJ)	0.05984
Light Fuel Oil (MJ)	0.3877
Gasoline (MJ)	0.004674

Coal Mining and Processing (per kg of coal)

Electricity (MJ)	0.19256

Transport requirements are incorporated into energy inputs in the data shown in the following table. These are first subtracted from the data and then converted into tonne-km factors based on conversion factors provided by NREL LCI database (NREL, 2005). Transport from steel to the distribution centre is estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Transport Energies (per kg of indicated product)

Iron ore by ship (MJ)	0.3456	Residual Oil
Iron ore by rail (MJ)	0.0392	Diesel
Coal by ship (MJ)	0.0902	Residual Oil
Coal by rail (MJ)	0.2695	Diesel
Limestone by truck (MJ)	0.1132	Diesel

Finally, CO_2e emissions reported in the steel LCI module also include those emissions due to fossil fuel combustion. Thus, combustion related CO_2e emissions for the unit processes removed from the steel LCI module must also be removed. Such emissions are calculated based on Environment Canada emission factors (Environment Canada, 2007).

Fiberglass Insulation

LCI data are taken from the ASMI LCI data set (Norris, 1999). Data quality is not adequate as only the total flows between the environment and the product system are presented. Further, unclear data labels such as ‘gas’ are presented and no transport data are provided. Modifications to the data include the following:

1) Dolomite and feldspar are assumed to be equivalent to limestone
2) ‘Gas’ is assumed to refer to natural gas
3) ‘Riversand’ is assumed to refer to sand
4) Sulphur input is removed due to unavailable LCI data

All transport requirements are estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Polystyrene Insulation

LCI data are taken from the NREL U.S. LCI database for high impact polystyrene. Data quality is sufficient for this study. Transport of polystyrene insulation to distribution centre is estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Ceramic Tiles

LCI data are taken from both the BEES LCI database and the NREL LCI database. Flow diagrams for ceramic tile production and energy requirements for the ceramic tile drying and firing are provided by BEES (Lippiatt, 2007). Styrene butadiene latex used as an adhesive in ceramic tiles is modeled using NREL LCI data for acrylonitrile butadiene styrene (NREL, 2005). All transportation requirements are estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Vinyl Flooring

LCI data are taken from both the BEES LCI database and the NREL LCI database. BEES quantifies inputs into the unit process (Lippiatt, 2007). Resin (95% PVC, 5% polyvinyl acetate) is assumed to be 100% PVC. Plasticizer is modeled as polypropylene. Styrene butadiene resin is modeled using NREL LCI data for acrylonitrile butadiene styrene. All transport requirements are estimated using StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Linoleum Flooring

LCI data are taken from the BEES LCI database (Lippiatt, 2007). Pine rosin/tall oil is assumed to be linseed oil. Wood flour and cork flour are modeled using NREL LCI data for Pacific Northwest plywood

(NREL, 2005). Acrylic lacquer is omitted due to unavailable LCI data. All transport requirements are estimated using StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Nylon Carpet

LCI data are taken from both the BEES LCI database and the Centre for Environmental Assessment of Product and Material Systems (CPM) (CPM, 2008; Lippiatt, 2007). BEES provides inputs for nylon broadloom carpet manufacturing (Lippiatt, 2007). ‘Stainblocker’ and ‘additives’ are omitted as inputs. Steam energy is omitted since its fuel source is not listed. LCI data for the production of nylon are taken from the CPM (CPM, 2008). The following modifications were made to the CPM data:

- Inputs less than 1% by mass are excluded
- ‘Hydro energy’ and ‘Nuclear Energy’ are quantified as electricity
- Sulphur input is omitted due to lack of available LCI data

All transport requirements (excluding bauxite) are estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Latex Paint

LCI data are taken from both the BEES LCI database and the NREL LCI database (Lippiatt, 2007; NREL, 2005). BEES provides inputs for virgin latex paint (i.e. no recycled content). The data includes several possible types of resin that are used in paint manufacture. Due to lack of LCI data, none could be modeled directly. Rather, vinyl acrylic was assumed to be the resin used, of which 80-95% is vinyl acetate and 5-20% is butyl acrylate. Vinyl acetate is produced similarly to polyethylene terephthalate as both are products of binding ethylene and acetic acid in the presence of oxygen (Han et al, 2004). Therefore the resin is assumed to be 100% polyethylene terephthalate, modeled using NREL LCI data for polyethylene terephthalate (NREL, 2005). All transport requirements are estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Plywood

LCI data are taken from the NREL LCI database U.S. Pacific Northwest plywood production (NREL, 2005). Data quality is sufficient for this study. Transport of plywood to distribution centre is estimated using StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Petroleum Products

All data for petroleum product manufacturing are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Other Intermediate Products

Caustic Soda

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Lime

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Oxygen

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Chlorine

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Iron Pellets

LCI data are taken from the ASMI data set for steel production (MES, 2003). Data includes iron ore mining and pelletizing. To separate the two processes, the iron ore mining energy requirements from StatsCan literature (StatsCan, 2007a) are subtracted from the aggregated data. What remains becomes the LCI module for iron pellet manufacturing. No transport is associated with this module.

Polyethylene

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study. Transport of polyethylene to distribution centre is estimated using StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Polypropylene

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Polyvinyl Chloride

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Flyash

LCI data are taken from the ASMI data set (CCMET et al, 1999). Only transport requirements are modeled as fly ash is a waste product of coal combustion.

Glass

LCI data are taken from CPM LCI database for glassworks (CPM, 2008). The data assumes a given recycled content of glass as input. Raw material inputs are scaled to reflect a 0% recycling scenario. Fuel inputs stay constant. All rock inputs are assumed to be limestone. Sodium sulphate is removed due to unavailable LCI data. All transport requirements are estimated from StatsCan literature (StatsCan, 2005a; StatsCan, 2005b).

Nitrogen

LCI data are taken from the NREL LCI database for nitrogen fertilizer production (NREL, 2005). ‘Unspecified energy’ is assumed to be natural gas.

Titanium Dioxide

LCI data are taken from various sources. Process energy for production of titanium dioxide is taken from the CPA LCI database (CPM, 2008). The data does not list the input of ilmenite ore. The ratio of 5 kg of ilmenite ore per 1 kg of titanium dioxide is taken from the ASMI LCI data set for latex paint (Venta, 1997).

Styrene Butadiene

LCI data are taken from the NREL LCI database for acrylonitrile butadiene styrene (NREL, 2005). LCI development methodology is identical to that for the SBS roofing membrane.

Primary Energy Resources

Natural Gas Extraction and Processing

LCI data are taken from the NREL LCI database (NREL, 2005). Aggregated data are provided for both natural gas extraction and processing and crude oil extraction. Data are allocated by mass. Data quality is sufficient for this study.

Crude Oil Extraction

LCI data are taken from the NREL LCI database (NREL, 2005). Aggregated data are provided for both natural gas extraction and processing and crude oil extraction. Data are allocated by mass. Data quality is sufficient for this study.

Bituminous and Sub-bituminous Coal Mining

LCI data are taken from the NREL LCI database (NREL, 2005). Data applies to both bituminous and sub-bituminous coal mining. Data quality is sufficient for this study.

Lignite Coal Mining

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Uranium Ore Mining and Uranium oxide Manufacturing

LCI data are taken from the NREL LCI database (NREL, 2005). Data quality is sufficient for this study.

Electricity Generation

Data is taken from Statistics Canada annual publication *Electricity Generation, Transmission and Distribution in Canada, 2005* (StatsCan, 2006d). The report lists the consumption of all primary resources used to generate electricity. The data are used to average fuel consumption by all primary resources per kWh electricity production in Canada. Electricity production from diesel, wood, light fuel oil, and 'others' are excluded as they constitute less than 1% of input.

Canadian and imported bituminous are amalgamated as 'bituminous' in this study; Canadian and imported sub-bituminous are amalgamated as 'sub-bituminous'. Average bituminous and sub-bituminous fuel consumption per kWh is calculated by adding total consumption of both Canadian and imported coal and dividing the total by the total electricity produced by both.

Primary Non-Energy Resources

Statistics Canada publications for metal and non-metal mining and quarrying (StatsCan, 2007a, StatsCan, 2007b) form the basis for the data for the following resources:

- Limestone
- Sandstone
- Sand and Gravel
- Clay and Shale
- Gypsum
- Talc
- Mica
- Salt
- Iron Ore
- Ilmenite ore

Talc and mica extraction is modeled using data in the 'Other Non-metallic mineral mining and quarrying' category. Ilmenite ore extraction is modeled using data in the 'Other metal mining' category. Data is developed by dividing fuel consumption from each industry by the total mineral extracted.

Bauxite Ore

LCI data are taken from the NREL LCI database for primary aluminum production (NREL, 2005). Data quality is sufficient for this study.

Softwood

LCI data are taken from the NREL LCI database for U.S Pacific Northwest plywood production. Data quality is sufficient for this study.

Jute

LCI data are taken from the NREL LCI database for cotton production (NREL, 2005).

Linseed Oil

LCI data are taken from the NREL LCI database for rapeseed oil production (NREL, 2005).

Transportation

NREL LCI Data

LCI data are taken from the NREL LCI database for the following transportation modes:

- Combination truck (i.e. transport truck)
- Barge
- Freighter
- Rail
- Natural Gas Pipeline
- Petroleum Pipeline
- Coal Slurry Pipeline

Average fuel consumption per tonne-kilometre is calculated for each transport mode.

Appendix H

Appendix H summarizes the alternate transport data used in process-based LCI when missing or inadequate data are identified. Table H1 lists total tonnage and average distance traveled by truck for various aggregate product groups. Table H2 shows the same for rail, particular for transport to British Columbia from other provinces. Table H3 summarizes the weighted transport factors for truck and rail used in this study. Note the average distance traveled by rail that is assumed for non-building products in this study is 743 km.

Table H1: Total Tonnage of Products Transported by Truck in Canada, 2003

Product	**Total Tonnes ('000)**	**Total Tonne-km ('000)**	**Average Distance Transported (km)**
Other coal and petroleum products	4,947	1,693,830	342.4
Rubber	973	371,323	381.6
Gravel and Crushed Stone	3,098	330,126	106.6
Salt	2,509	704,521	280.8
Glass and Glass Products	1,066	600,398	563.2
Non-ferrous metal, basic form	1,212	810,939	669.1
Non-metallic minerals	4,363	1,256,601	288.0
Plastics - basic shapes and articles	1,042	745,864	715.8
Inorganic chemicals	1,729	643,789	372.3
Total Iron and Steel	9,322	3,427,276	413.6
Natural Sands	1,981	396,958	200.4
Non-metallic mineral products	5,332	1,989,530	373.1
Textile and Textile Articles	364	179,683	493.6
Chem. Products and preparations	3,270	1,243,098	380.2
Veneer Sheets	1,381	735,592	532.7
Lumber	8,074	4,189,461	518.9

Source: StatsCan, 2005a

Table H2: Total tonnage of products transported by Rail to British Columbia in 2003, by Province

	Atlantic	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	British Columbia	Total Weighted Distance (km)
Distance to BC (km)	5,970	4,991	4,531	2,152	1,597	1,164	0	
Product Transported (tonnes)								
Refined Petroleum Products	0	1,081	36,891	77	0	167,553	56	1,788
Plastics and Rubber	2,484	8,749	21588	357	0	164,212	322	1,761
Sand, Gravel, and Crushed Stone	0	13,523	91	0	0	19,941	70,335	877
Salt	0	0	44	0	64,082	49,253		1,410
Other Non-Metallic minerals	107	44,397	7,533	1,149	5,294	2,980	201,946	1,028
Other Non-metallic mineral products	2,147	41,211	14,262	0	0	20,110	8,783	3,543
Aluminum	0	16,107	332	0	0	0	0	4,982
Copper, Alum and all non-ferrous	1,728	20,315	12,043	4,353	0	1696	9596	
Other Basic Chemicals	331	35,634	21,006	37,330	16,950	16,70154	112,932	1,228
Iron and Steel	0	4,309	88,435	82	80,515	2,8441	44	2,894
Chem. Products and Preparations	0	6,532	8,947	19	0	15,277	67	2,949
Veneer Wood	1,517	11,884	14,349	2,165	6,495	72,836	90,040	1,170

Source: StatsCan, 2005b

Table H3: Final Truck and Rail Transportation Requirements for Products

Product	Transport Requirements per kg of product (tonne-km)	
	Truck	**Rail**
Aluminum	0.1943	3.5352
Caustic Soda	0.2939	0.2139
Ceramic Tiles	0.3001	0.6931
Chlorine	0.0547	0.8045
Clay	0.1301	0.5171
EPDM Membrane	0.0979	1.3093
Fiberglass Insulation	0.3001	0.6931
Glass	0.5632	0.0000
Iron Ore	0.0000	0.9430
Latex Paint	0.3731	0.0000
Limestone	0.0662	0.3568
Linoleum Flooring	0.3001	0.6931
Mortar	0.3001	0.1845
Nylon Carpet	0.4936	0.0000
Oxygen	0.0547	0.8045
Plywood	0.1648	0.8082
Polyethylene	0.1837	1.3093
Polypropylene	0.1837	0.7010
Polystyrene Insulation	0.1837	1.3093
Polyvinyl acetate	0.1837	0.7010
PVC	0.1837	0.7010
Salt	0.1836	0.3264
Sand	0.1246	0.3319
Sandstone	0.0662	0.3568
SBS Roofing Membrane	0.0979	1.3093
Steel Products	0.2635	1.0499
Styrene Butadiene	0.0979	1.3093
Titanium Dioxide	0.2939	0.2139
Vinyl Flooring	0.1837	1.3093
Window	0.5632	0.0000

Appendix I

Table I1: Input-Output Table used in this study

NAICS Code	1130	2111	2121	2122	2123	2211	221A	31A0	3210	3221	3222
Description	Forestry and Logging	Oil and Gas Extraction	Coal Mining	Metal Ore Mining	Non-Metallic Mineral Mining and Quarrying	Electric Power Generation, Transmission and Distribution	Natural Gas Distribution, Water, Sewage and Other Systems	Textile and Textile Product Mills	Wood Product Manufacturing	Pulp, Paper and Paperboard Mills	Converted Paper Product Manufacturing
Forestry and Logging	0.092187	9.4E-05	0.000126	0.000124	5.88E-05	0.000434	0.000101	0.000144	0.248718	0.060851	0.000194
Oil and Gas Extraction	0.000878	0.046412	0.007803	0.009269	0.026465	0.049865	0.062246	0.006692	0.005431	0.018794	0.006529
Coal Mining	3.89E-06	5.58E-07	6.25E-07	1.93E-06	2.11E-06	0.039864	0	0	2.43E-05	0.000125	0
Metal Ore Mining	4.53E-05	0.000381	0.000165	0.010299	0.000233	0.004118	5.35E-05	4.04E-05	3.81E-05	8.34E-05	7.35E-05
Non-Metallic Mineral Mining and Quarrying	5.48E-05	0.000937	0.000285	0.006123	0.009943	5.94E-06	1.52E-05	2.84E-05	4.62E-05	0.000839	7.85E-05
Electric Power Generation, Transmission and Distribution	0.00418	0.011123	0.032019	0.037331	0.019662	8.54E-05	0.004431	0.014789	0.014981	0.073318	0.010527
Natural Gas Distribution, Water, Sewage and Other Systems	0.000267	5.41E-05	0.000857	0.0005	0.003581	0.000217	0.001408	0.001219	0.000971	0.004552	0.001163
Textile and Textile Product Mills	0.005025	0.000445	0.000634	0.000439	0.003678	5.6E-05	0.000422	0.156582	0.000467	0.002812	0.00772
Wood Product Manufacturing	0.000889	0.000338	0.00078	0.000398	0.000459	0.000131	0.00032	0.000706	0.132092	0.086345	0.006701
Pulp, Paper and Paperboard Mills	0.000964	0.000506	0.000546	0.000448	0.000239	0.000124	0.000564	0.004721	0.001507	0.094715	0.243538
Converted Paper Product Manufacturing	0.002652	0.000964	0.001036	0.000734	0.00288	0.000251	0.001297	0.008631	0.003891	0.015975	0.106768
Petroleum and Coal Products Manufacturing	0.029148	0.004723	0.041536	0.019714	0.026319	0.01503	0.012971	0.002985	0.004769	0.014056	0.00359
Basic Chemical Manufacturing	0.003985	0.002347	0.001544	0.009011	0.00247	0.000134	0.000955	0.011414	0.001774	0.037385	0.003453
Resin, Synthetic Rubber, and Artificial and Synthetic Fibres and Filaments Manufacturing	0.001252	0.000477	0.000731	0.000748	0.000341	5.65E-05	0.000373	0.143442	0.014764	0.003578	0.007623
Miscellaneous Chemical Product Manufacturing	0.009413	0.002607	0.024916	0.012812	0.007855	0.000342	0.002032	0.017619	0.005481	0.012611	0.02188
Plastic Product Manufacturing	0.007767	0.002234	0.004383	0.002097	0.00221	0.000228	0.001988	0.005289	0.005055	0.005434	0.01536
Rubber Product Manufacturing	0.005292	0.001597	0.002122	0.001219	0.000768	0.000148	0.001384	0.004842	0.001042	0.001911	0.001566
Non-Metallic Mineral Product Manufacturing	0.001478	0.000529	0.000595	0.004088	0.000886	0.00014	0.000445	0.001417	0.002989	0.005845	0.00082
Primary Metal Manufacturing	0.008245	0.001832	0.001675	0.015154	0.001217	0.003702	0.000493	0.000886	0.001839	0.003102	0.003809
Fabricated Metal Product Manufacturing	0.025303	0.006735	0.00999	0.008393	0.006206	0.000591	0.004748	0.003578	0.007351	0.008033	0.005116
Rail Transportation	0.001009	0.000382	0.005745	0.004229	0.00405	0.002545	0.000254	0.001322	0.00639	0.012433	0.003242
Water Transportation	0.005328	4.5E-05	0.000151	0.000507	0.005067	0.000259	3.07E-05	0.000146	0.000683	0.001954	0.000353
Truck Transportation	0.018207	0.001161	0.004124	0.008008	0.003342	0.007523	0.000729	0.005104	0.020366	0.039495	0.010902

Pipeline Transportation	0.000274	0.001028	0.001263	0.000683	0.002131	0.001224	0.006928	0.001489	0.000962	0.003835	0.001307

Code	3241	3251	3252	325A	3261	3262	327A	3310	3320	4820	4830
Description	Petroleum and Coal Products Manufacturing	Basic Chemical Manufacturing	Artificial and Synthetic Fibres and Filaments Manufacturing	Miscellaneous Chemical Product Manufacturing	Plastic Product Manufacturing	Rubber Product Manufacturing	Non-Metallic Mineral Product Manufacturing	Primary Metal Manufacturing	Fabricated Metal Product Manufacturing	Rail Transportation	Water Transportation
Forestry and Logging	0.000134	0.000279	0.00013	0.000254	0.000126	0.000266	0.000403	0.000131	0.000124	0.000124	6.28E-05
Oil and Gas Extraction	0.707146	0.189168	0.033	0.007211	0.003059	0.006845	0.048089	0.014568	0.005105	0.00087	0.005605
Coal Mining	1.21E-05	0	0	0	0	0	0.003471	0.011274	9.56E-07	0	0
Metal Ore Mining	4.87E-05	0.000105	2.87E-05	7.41E-05	3.87E-05	0.000112	0.001221	0.171558	3.77E-05	8.44E-05	2.81E-05
Non-Metallic Mineral Mining and Quarrying	0.001891	0.008945	0.000101	0.001739	6.22E-05	0.000495	0.128648	0.002436	6.79E-05	6.08E-05	2.35E-05
Electric Power Generation, Transmission and Distribution	0.007467	0.047586	0.022997	0.006762	0.017477	0.01239	0.049928	0.029523	0.008921	0.002948	0.001714
Natural Gas Distribution, Water, Sewage and Other Systems	0.000247	0.005583	0.003928	0.000833	0.00059	0.000905	0.008126	0.002799	0.001087	0.001003	0.001723
Textile and Textile Product Mills	0.000121	0.000204	0.000502	0.006587	0.004462	0.034745	0.000701	0.0004	0.000503	0.000482	0.002533
Wood Product Manufacturing	0.001517	0.000789	0.001115	0.002028	0.006542	0.00113	0.008958	0.000967	0.004111	0.000404	0.000289
Pulp, Paper and Paperboard Mills	0.00069	0.000551	0.000264	0.001566	0.001577	0.000839	0.021796	0.000482	0.000611	0.000177	0.000325
Converted Paper Product Manufacturing	0.001657	0.002313	0.002741	0.020857	0.013234	0.004723	0.016766	0.001544	0.005096	0.000154	0.002059
Petroleum and Coal Products Manufacturing	0.054365	0.114208	0.020796	0.018421	0.00212	0.003042	0.020207	0.006325	0.003814	0.081168	0.088473
Basic Chemical Manufacturing	0.012268	0.173672	0.399395	0.124745	0.017436	0.027021	0.016859	0.006375	0.003358	0.000189	0.000652
Resin, Synthetic Rubber, and Artificial and Synthetic Fibres and Filaments Manufacturing	0.000988	0.014259	0.097012	0.068789	0.23758	0.093155	0.009346	0.001041	0.0044	0.000103	0.000266
Miscellaneous Chemical Product Manufacturing	0.01399	0.013768	0.025601	0.089052	0.051811	0.037721	0.018473	0.002863	0.015292	0.000732	0.002111
Plastic Product Manufacturing	0.001302	0.007412	0.004466	0.041398	0.060067	0.013636	0.020232	0.002286	0.007453	0.000675	0.002796
Rubber Product Manufacturing	0.000353	0.000657	0.001053	0.000764	0.003105	0.112144	0.003148	0.001398	0.002145	0.00055	0.001999
Non-Metallic Mineral Product Manufacturing	0.001347	0.001528	0.000289	0.006629	0.007469	0.001561	0.30635	0.009752	0.005985	0.000502	0.000635
Primary Metal Manufacturing	0.000606	0.010151	0.000534	0.003027	0.003746	0.012919	0.013441	0.251887	0.231793	0.005695	0.000413
Fabricated Metal Product Manufacturing	0.001236	0.002153	0.002019	0.012368	0.012214	0.013245	0.018402	0.032384	0.107841	0.003808	0.003127
Rail Transportation	0.001051	0.003664	0.00351	0.003175	0.001799	0.002139	0.012192	0.004473	0.003182	0.014277	0.002838
Water Transportation	0.000116	0.000403	0.000378	0.000346	0.00018	0.000242	0.001295	0.000466	0.000328	4.36E-05	0.195474
Truck Transportation	0.004783	0.015021	0.011976	0.010855	0.005569	0.012001	0.038327	0.01439	0.010138	0.001999	0.004434
Pipeline Transportation	0.024554	0.011216	0.004905	0.000906	0.0006	0.001533	0.008623	0.002936	0.001038	0.000621	0.002072

Code	4840	4860
Description	Truck Transportation	Pipeline Transportation
Forestry and Logging	5.13E-05	4.66E-05
Oil and Gas Extraction	0.001475	0.010419
Coal Mining	0	0
Metal Ore Mining	1.21E-05	2.3E-05
Non-Metallic Mineral Mining and Quarrying	0.000144	3.72E-05
Electric Power Generation, Transmission and Distribution	0.001534	0.0219
Natural Gas Distribution, Water, Sewage and Other Systems	0.000248	0.000333
Textile and Textile Product Mills	0.000452	0.00011
Wood Product Manufacturing	0.000482	0.00013
Pulp, Paper and Paperboard Mills	7.71E-05	0.000225
Converted Paper Product Manufacturing	0.00046	0.000307
Petroleum and Coal Products Manufacturing	0.118784	0.003515
Basic Chemical Manufacturing	0.00015	0.0003
Resin, Synthetic Rubber, and Artificial and Synthetic Fibres and Filaments Manufacturing	7.93E-05	0.000248
Miscellaneous Chemical Product Manufacturing	0.002944	0.000554
Plastic Product Manufacturing	0.000647	0.000506
Rubber Product Manufacturing	0.004295	0.000356
Non-Metallic Mineral Product Manufacturing	0.000364	0.000153
Primary Metal Manufacturing	9.19E-05	0.00027
Fabricated Metal Product Manufacturing	0.002465	0.001246
Rail Transportation	0.005571	0.000132
Water Transportation	0.001895	1.83E-05
Truck Transportation	0.158914	0.000251
Pipeline Transportation	0.000838	0.000144

Appendix J

Appendix J presents alternate fuel consumption data for industries not included in CIEEDAC data.

Table J1: Fuel Consumption Factor Development for Truck Transportation Industry

Average transport distance in 2003	794 km
Total tonnage in 2004	604.3 million
Estimated tonne-km in 2004	479.8 billion
Fuel consumption (L/tonne-km)	0.02722
Total fuel consumed (L) - Gasoline - Diesel	 2.351 billion 10.710 billion
Total industry output (‘000 $)	32,696,942
Fuel Consumption Factor (L/'000 $) - Gasoline - Diesel	 71.903 327.56

Table J2: Fuel Consumption Factor Development for Rail Transportation Industry

Total diesel consumed (kilolitres)	2,102,817
Industry Output (‘000 $)	8,579,633
Diesel Consumption Factor (L/’000 $)	245.09

Table J3: Fuel Consumption Factor Development for Water Transportation Industry

1998 Fuel consumption	
- Residual Fuel Oil	1051 kilotonnes (1,112,676 kilolitres)
- Gasoline	33 kilotonnes (44,652 kilolitres)
Total tonnage in 1998 (megatonnes)	376.1
Total tonnage in 2004 (megatonnes)	452.3
Estimated 2004 Fuel Consumption	
- Residual Fuel Oil	1,338,110 kilolitres
- Gasoline	53,699 kilolitres
Total industry output in 2004 ('000 $)	3,234,903
Fuel Consumption factor (L/'000 $)	
- Residual Fuel Oil	413.6
- Gasoline	16.60

Table J4: Fuel Consumption Factor Development for Crude Oil and Refined Petroleum Product Pipeline Transport

Total m3-km transported in 2004	146,379,677
Total tonne-km transported in 2004	129,929,865
Electricity Consumption (kWh)	1,935,955
Industry Output (‘000 $)	6.82E+06
Electricity Consumption Factor	0.2839

Table J5: Fuel Consumption Factor Development for Natural Gas Distribution and Pipeline Transport

	Distribution	Pipeline	Total
Tonne-km transported in 2004	N/A	N/A	1.95246E+11
System length (km)	2.45E+05	6.28E+04	3.08E+05
Estimated tonne-km	1.55E+11	3.98E+10	1.95E+11
Natural Gas Consumed (m3)	2.08E+09	5.33E+08	2.61E+09
Industry output ('000 $)	4.75E+06	6.82E+06	
Natural Gas Consumption Factor (m3/'000 $)	437.7	78.1	

Table J6: Fuel Consumption Factor Development for Forestry and Logging Industry

Totals	**1 m3 of wood**	**2004 total production**	**Fuel Consumption Factor (/‘000 $)**
Electricity (kWh)	0.05566	11,601,362	0.867
Gasoline (L)	0.02445	5,097,371	0.381
Diesel (L)	2.79475	582,426,176	43.5

Total output from the industry is $13,364 million
Total production of wood is 208.4 million m3

Table J7: Fuel Consumption Factor Development for Coal Mining

	1 kg Coal	**2004 total production**	**Fuel Consumption Factor (/ ‘000 $)**
Coal (kg)	4.30E-04	28,376,990	17.74
Distillate oil (L)	8.75E-03	577,693,128	361.16
Electricity (kWh)	3.88E-02	2,558,318,943	1599.40
Gasoline (L)	8.34E-04	55,018,393	34.40
Natural gas (m3)	1.60E-04	10,541,437	6.59
Residual oil (L)	8.34E-04	55,018,393	34.40

Total output from the industry is $1,600 million
Total production of coal in 2004 is 65,993 kilotonnes

Table J8: Fuel Consumption Factor Development for Oil and Gas Extraction

	1 L Crude Oil (/L)	**1 m3 Natural Gas**	**2004 total production**	**Fuel Consumption Factor (/'000 $)**
Diesel (L)	1.09E-03	1.02E-03	385,903,561	4.219148549
Electricity (kWh)	3.29E-02	4.55E-02	14,813,433,242	161.9577574
Gasoline (L)	5.80E-04	5.63E-04	209,305,393	2.288371072
Natural Gas (m3)	2.76E-02	5.03E-02	15,080,723,531	164.8800871
Residual Fuel Oil (L)	6.73E-04	6.48E-04	241,607,432	2.641534696
Crude Oil (L)	1.05E-04	9.59E-05	36,563,009	0.399749528

Total output from the industry is $91,465 million

Total production of crude oil in 2004 is 1.49E+11 L

Total production of natural gas in 2004 is 2.18E+11 m^3

Appendix K

Table K1: Total Product Quantities in Medical Sciences Building Product System, PS and PMR-based LCI

Product	PMR-Based LCI Results	PS-Based LCI Results
Natural Gas (m^3)	181,000	172,530
Distillate Fuel Oil (L)	39,632	37,531
Gasoline (L)	4,802	4,548
Residual Fuel Oil (L)	25,098	23,768
Crude Oil (L)	101,241	95,875
LPG (L)	464	439
Petroleum Coke (L)	9,336	8,842
Asphalt/Road Oil (kg)	2,253	2,134
Light Fuel Oil (L)	2,619	2,480
Kerosene (L)	0.05	0.05
Ethylene (kg)	5,316	5,316
Propylene (kg)	2,493	2,493
Pygas (kg)	2,925	2,925
Benzene (kg)	8,731	8,731
White Mineral Oil (kg)	16	16
Butadiene (kg)	1,100	1,100
Bituminous Coal (kg)	134,420	133,884
Subbituminous coal (kg)	43,676	42,005
Lignite Coal (kg)	18,937	18,242
Uranium (kg)	2.61	2.51
Electricity (kWh)	873,778	840,575
Limestone (kg)	795,287	795,287
Sandstone (kg)	11,024	11,024
Sand and Gravel (kg)	4,581,677	4,581,677
Clay and Shale (kg)	395,767	395,767
Gypsum (kg)	164,808	164,808
Talc (kg)	278	278
Mica (kg)	256	256
Salt (kg)	8,104	8,104
Iron (kg)	148,251	148,251
Bauxite (kg)	52,326	52,326
Ilmenite (kg)	17,462	17,462
Softwood (kg)	8,774	8,774
Linseed Oil (kg)	1,835	1,835
Jute (kg)	643	643
Caustic Soda (kg)	3,510	3,510
Titanium Dioxide (kg)	3,492	3,492

Lime (kg)	21,771	21,771
Oxygen (kg)	24,555	24,555
Chlorine (kg)	27	27
Nitrogen (kg)	166	166
Iron Pellet (kg)	89,016	89,016
Styrene Butadiene (kg)	998	998
Polyethylene (kg)	541	541
Polypropylene (kg)	829	829
Polyvinyl Chloride (kg)	50	50
PVA Resin (kg)	6,755	6,755
Glass (kg)	9,536	9,536
Cement (kg)	624,618	624,618
Concrete (m^3)	1,956	1,956
Mortar (kg)	1,984	1,984
Fly Ash (kg)	66,892	66,892
Clay Brick (kg)	192,568	192,568
Gypsum Board (m^2)	10,852	10,852
Window Glass (m^2)	787	787
Aluminum (kg)	10,269	10,269
SBS roofing membrane (kg)	6,472	6,472
EPDM (kg)	313	313
Steel Rebar (kg)	299,909	299,909
Galvanized Studs (kg)	45,399	45,399
Galvanized Sheet (kg)	6,998	6,998
Screws, Nuts, and Bolts (kg)	1,292	1,292
Steel Nails (kg)	102	102
Fiberglass insulation (m^2)	907	907
Polystyrene Insulation (kg)	6,137	6,137
Ceramic Tile (m2)	467	467
Vinyl Flooring (m2)	63	63
Linoleum Flooring (m2)	2,053	2,053
Nylon Carpet (m2)	465	465
Latex Paint (kg)	25,851	25,851
Plywood (kg)	7,975	7,975
Combination Truck (tonne-km)	853,542	810,865
Barge (tonne-km)	328,075	311,671
Freighter (tonne-km)	1,325,293	1,259,028
Rail (tonne-km)	834,386	792,667
Pipeline-NG (tonne-km)	217,107	206,252
Pipeline-Petro (tonne-km)	24,788	23,549
Pipeline- Coal (tonne-km)	2,187	2,077

Table K2: Total Product Quantities in Medical Sciences Building Product System, I/O-based LCI

Electricity (kWh)	1,169,649
Natural Gas (m³)	220,963
Heavy Fuel Oil (L)	27,243
Diesel (L)	44,729
Light Fuel Oil (L)	665
Propane (L)	6,780
Petroleum Coke (kg)	51,112
Coal (kg)	185,927
Sub Bit (kg)	33,723
Lignite (kg)	23,147
Coal Coke (kg)	1,073
Coal Oven Gas (m³)	17,740
Steam (MJ)	22,782
Refinery Fuel Gas (L)	64,274
Wood Waste (kg)	415
Spent Pulping Liquor (kg)	3,069
Waste Fuel (MJ)	68

Appendix L

This Appendix lists all recycled product unit processes considered in this study. CO_2e emissions are based on factors taken from the Environment Canada (ECGSS, 2007).

Glass and Fiberglass Recycling, 1 kg

Electricity (kJ)	1,080
Coal (kJ)	968
RFO (kJ)	2,527
Total (MJ)	4.57
Base Case Energy (MJ)	9.44
Ratio	**48.5%**

Source: Chunfa et al, 2007

Aluminum Recycling, 1 kg

Lignite (MJ)	0.750
NG (MJ)	12.098
RFO (MJ)	1.405
Bit. Coal (MJ)	1.314
Electricity (MJ)	0.515
LFO (MJ)	0.003
Chlorine (kg)	0.002
Lime (kg)	0.008
Salt (kg()	0.014
Nitrogen (kg)	0.002
Total (MJ)	16.090
Base Case Energy (MJ)	106.070
Ratio	**15.2%**

Source: CPM, 2008

Plywood Recycling, 1 kg

Base Case Manufacturing	9.69
Recycled Manufacturing	6.63
Ratio	**68.4%**

Source: Gao et al, 2001

SBS Roofing Membrane Recycling, 1 kg

Conserved Energy by Recycling (MJ)	25.7
Base Case Manufacturing (MJ)	88.2
Recycled Manufacturing (MJ)	62.5
Ratio	**70.9%**

Source: Morris, 1996

Polypropylene Recycling, 1 kg

Conserved Energy by Recycling (MJ)	62.92
Base Case Manufacturing (MJ)	83.81
Estimated Recycled Manufacturing (MJ)	20.89
Ratio	**24.9%**

Source: Morris, 1996

Polystyrene, 1 kg

Electricity (kWh)	1.02
Natural Gas (m3)	1.22
Total (MJ)	50.2
Base Case Energy (MJ)	88.5
Ratio	**56.7%**

Source: Noguchi et al, 1998

Concrete and Clay Brick Crushing Energy per kg

Electricity (kWh)	0.003

Source: CCMET, 1999

Gypsum and Linoleum Crushing Energy per kg

Electricity (kWh)[1]	0.00198

Source: Venta, 1997

Appendix M

Table M1 lists the HHV for all fuels considered in this study.

Table M1: HHV of fuels used in this study

Fuel	**Value**	**Units**
Distillate Fuel Oil	38.8	MJ/L
Diesel	38.3	MJ/L
Residual Fuel Oil	42.5	MJ/L
Natural Gas	38.26	MJ/m3
Propane	25.31	MJ/L
Kerosene/Aviation Fuel Oil	37.68	MJ/L
Light Fuel Oil	38.8	MJ/L
Middle Distillates	38.68	MJ/L
Canadian Bituminous Coal	19.36	MJ/kg
Imported Bituminous Coal	28.7	MJ/kg
Canadian Sub-bituminous Coal	18.45	MJ/kg
Imported Sub-bituminous Coal	20.15	MJ/kg
Lignite Coal	15.13	MJ/kg
Gasoline	35	MJ/L
Crude Oil	38.52	MJ/L
Petroleum Coke	33.52	MJ/kg
Coal Coke	28.83	MJ/kg
Electricity	3.6	MJ/kWh
Liquefied Natural Gas	22.956	MJ/L
Uranium	704.547	MJ/g
Asphalt/ Road Oil	44.46	MJ/kg
Bitumen	42.8	MJ/L
Softwood	20	MJ/kg
Coke Oven Gas	19.14	MJ/m3
Refinery Gas	42.5	MJ/L
Wood Waste	18	MJ/kg
Spent Pulping Liquor	14	MJ/kg