EMERGY-BASED SUSTAINABILITY RATING SYSTEM FOR BUILDINGS: CASE STUDY OF CANADA

by

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Abstract

The building and construction industry significantly contributes to the global environmental problems as it accounts for 30-40% of energy and material consumption of the society and around 30% of the global greenhouse gas emissions. Considering growing population, resource scarcity and environmental effects of the building industry on Earth, there is an urgent need for paradigm shift toward sustainability and green buildings. However, studies show that 28-35% of the current LEED-certified green buildings actually use more energy than conventional buildings.

This thesis addresses weaknesses in current green building rating systems in North America, by implementing the “emergy” methodology. Emergy measure provides a holistic method to estimate the true value of environmental resources and services that was previously used to make a product/service. In this thesis, emergy methodology is used to assess the environmental and associated socioeconomic impacts of construction projects over lifecycle of buildings, including: resource extraction, manufacturing, transportation, construction, operation and maintenance, demolition and end of life scenarios (recycle, reuse and landfill). The main objective of this research is to develop an emergy-based sustainability rating system for buildings in Canada, named the “Em-Green sustainability rating system”. This sustainability evaluation system is a user-friendly framework for building and construction industry in Canada that covers the Triple Bottom Line (TBL) of sustainability (i.e.: environmental, social, and economical). The Em-Green sustainability fills the gap of a comprehensive building rating system that covers complete life-cycle of buildings (Cradle-to-Cradle/Grave approach) based on local practices in Canada. The framework developed for

Em-green sustainability rating system can be adopted for other nations and can be expanded to develop a global sustainability measure for the built environment.

Preface

Part of Chapter 2 of the research thesis has been published in the Canadian Society of Civil Engineering (CSCE) annual conference proceeding 2012, titled “Em-green building rating system: A sustainability measure for Canadian construction projects based on Emergy methodology”. Also, a version of Chapter 2 has been published in the 7th biennial emergy research conference, Gainesville, Florida, USA, titled “An Emergy-based sustainability rating system for Canadian Construction projects”.

Part of Chapter 3 has been published as a journal article titled “Sustainable materials selection for Canadian construction industry: an emergy-based life-cycle analysis (Em-LCA) of conventional and LEED suggested construction materials” in the Journal of Sustainable Development.

Part of Chapter 4 has been submitted to the Journal of Environmental Management, titled “Emergy accounting for regional studies: Case study of Canada”.

A journal article based on Chapter 5 and 6 of the thesis is under preparation for submission to the Journal of Building and Environment.

All of the papers are written by Navid Hossaini Fard under the supervision of Dr. Kasun Hewage.

The University of British Columbia (Okanagan) Behavior Research Ethics Board’s Ethics certificate was received for this research. The UBC-BREB number is H10-01000.

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List of Abbreviations

ATHENA	Athena impact estimator for buildings
BEPAC	Building environmental performance assessment criteria
BREEAM	Building research establishment environmental assessment method
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
C&D wastes	Construction and demolition wastes
DALY	Disability adjusted life year
ED	Emergy density
EIR	Emergy investment ratio
ELR	Environmental loading ratio
EME	Engineering, management and education
Em$	Emergy to money ratio
ESI	Emergy sustainability index
EpP	Emergy per person
EUV	Emergy unit value (transformity)
EYR	Emergy yield ratio
GBTool	Green building tool
GDP	Gross domestic product
GEM	Global environmental method
GIS	Geographic Information Systems
GHG	Greenhouse gas
HK-BEAM	Hong Kong building environmental assessment method

HQAL	Housing quality assurance law
HVFA	High volume fly ash
IECC	International energy conservation code
IEQ	Indoor environmental quality
ILBI	International living building institute
LBC	Living building challenge
LCA	Life cycle assessment
LCCBA	Life cycle cost benefit analysis
LCI	Life cycle inventory
LEED	Leadership in energy and environmental design
LEED-EB	LEED for existing buildings
LEED-NC	LEED for new construction and major renovation
LEED-RRM	LEED suggested rapidly renewable materials
LPG	Liquefied petroleum gas
MT	mega tonne
MSS	Maintainability scoring system
MSW	Municipal solid wastes
NABERS	National Australian built environment rating system
NO_x	Nitrogen oxides
Sej	solar emergy joule, solar emjoule
SO_x	Sulfur oxides
TBL	Triple bottom line
UN	United Nations

US EPA	United States environmental protection agency
US DOE	United States department of energy
UGGBC	United States green building council
VOC	Volatile Organic Compound

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Last, but not least, I greatly acknowledge the invaluable support of my parents and beloved brothers, Hamid and Vahid.

To my family

1 Chapter: Introduction

In this chapter, background information is provided about the current status of construction industry in Canada, the concept of green building is discussed and a comprehensive literature review of green building rating systems is provided. Also, an introduction is provided to the e*m*ergy (spelled with an 'm') methodology and the objective of this research thesis is defined.

1.1 Construction and building industry in Canada

Banging hammers and swinging cranes at construction sites across Canada are indicators of economic and social trends in this country. Construction is very active all over Canada (Statistics Canada, 2011b). After oil and gas, building and construction is one of Canada's largest industries, providing both infrastructure and employment for the Canadians. It consists of residential, commercial and industrial components. Construction is very dynamic across Canada and Canadian investment in buildings and public infrastructure projects is increasing (Statistics Canada, 2011b). Statistics Canada data shows that the construction industry provided 1.188 million direct jobs in 2007 over 270,000 firms. The construction firms produced over $180 billion in goods and services and contributed over $76.5 billion to Canada's GDP in 2007 (Statistics Canada, 2012). Figure 1.1 illustrates number of construction projects in Canada from 1995 to 2009. During this period, the construction sector contributed around 6% ($69 billion) each year to Canada's GDP. New opportunities in construction have drawn people from other industries, such as farming, manufacturing, and accommodation and food services (Statistics Canada, 2011a).

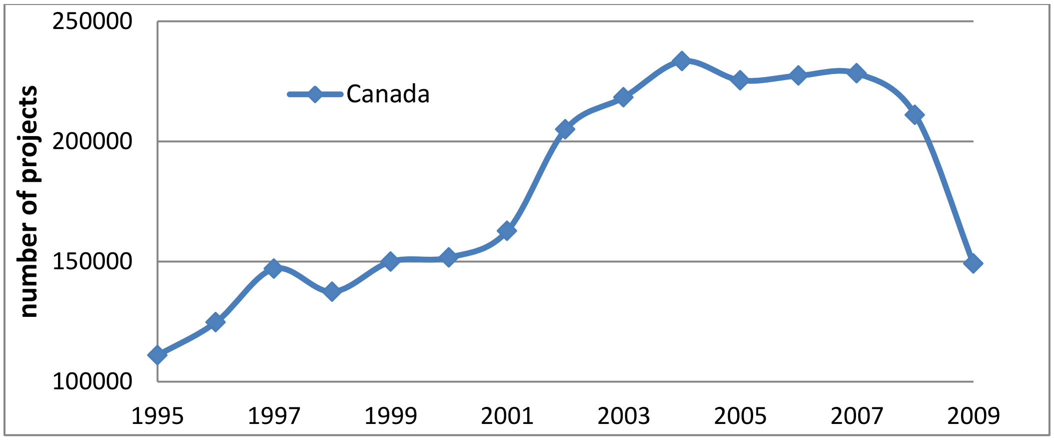


Figure 1.1 Construction projects in Canada, 1995-2009 (Statistics Canada, 2011a)

During the financial crisis in 2009, the construction sector was affected as all other sectors in Canada. After the recession, construction industry is still recovering. More jobs are being created in this sector as the demand for buildings and public infrastructure is uprising, especially in the western provinces.

Due to the size and type of activities in the construction, this industry is among the biggest energy consumer and environmental emitter in Canada. Figure 1.2 shows the energy consumption and emissions in Canada between 1990 and 2007.

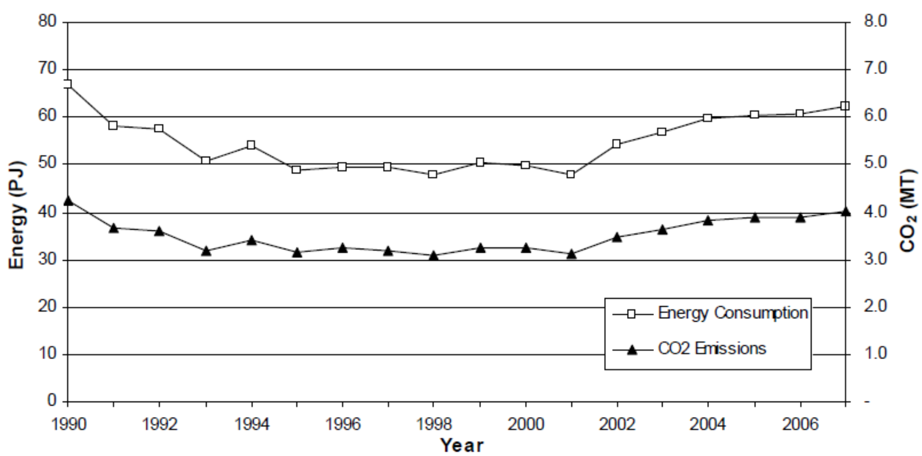


Figure 1.2 Canadian construction sector energy consumption and CO2 emissions (Environmental Canada, 2008)

Canadian construction sector energy consumption is increasing rapidly since 2000. Consequently, CO_2 emission is increasing annually since 2000 and reached to more than 6.2 MT in 2007.

One of the main reasons for the increase in construction activities, higher energy consumption, and more emissions is the growing population rate in Canada. According to Statistics Canada, population in Canada is increasing at a steep slope, estimated to reach over 42 million in 2050. It is more than 23% increase from 2012 (Statistics Canada, 2011c). Also, the typically cold Canadian climate is recognized as generally inhospitable, as a result Canadians spend about 90% of their time in buildings (US EPA, 1978).

As the Canadian population increases, the need for public infrastructure, including buildings increases exponentially. The building industry consumes a large portion of the limited resources in the world. It accounts for 30-40% of all natural resources used in developed countries such as Canada. This includes 40% of all material, 30% of energy, and 70% of all electricity consumption in the world (Roodman and Lenssen, 1995). Buildings are not only a major consumer of limited natural resources, but also one of the biggest polluters on the global scale. According to United States Green Building Council (USGBC 2007), the building sector accounts for 30% of all greenhouse gas emissions and 45-60% of land fill waste. This makes buildings the biggest CO2 emission sector, ahead of transportation and industrial sectors.

According to a report prepared for Industry Canada (Lucuik, 2005), the construction industry in Canada accounts for:

- 33% of Canada's energy production
- 50% of the extracted natural resources

- 25% of Canadian landfill waste
- 10% of airborne particulates
- 35% of greenhouse gases

Considering the growing population, resource scarcity, and environmental effects of the building industry, building and construction industry needs a paradigm shift towards sustainability and green practices since on average green buildings consume 30% less energy and have 35% less carbon emissions (USGBC, 2011).

1.2 What is a green building?

The need for more buildings, as global population increases, is undeniable. Since buildings consume enormous amounts of limited natural resources, switching towards sustainable buildings is an urgent need. There are various definitions for sustainable and/or green buildings with slight variations. For instance, Yudelson (2008, p.13) defined green building as a “high-performance property that considers and reduces its impact on the environment and human health.” A widely accepted definition of green building is provided by the United States Environmental Protection Agency (US EPA) as “the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction”, as shown in Figure 1.3 (US EPA, 2010a). In general, green building is also known as a sustainable or high performance building.

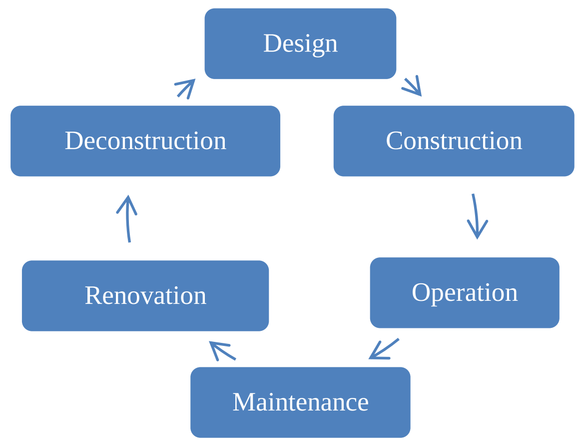


Figure 1.3 Green building lifecycle (US EPA, 2010a)

The built environment has a vast impact on the natural environment, human health, and the economy (US EPA, 2010b). By adopting green building strategies and moving toward 'sustainable development', construction industry can maximize both economic and environmental performance.

Sustainable development, also referred to as Triple Bottom Line (TBL) approach, defined by the United Nation in 1987, is a pattern of resource use that "aims to meet human needs while preserving the environment, so that these needs can be met not only in the present, but also for generations to come; to meet the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). During the 2005 World Summit, it was noted that achieving sustainable development goals requires reconciliation of environment, social and economic equity, as shown in Figure 1.4.

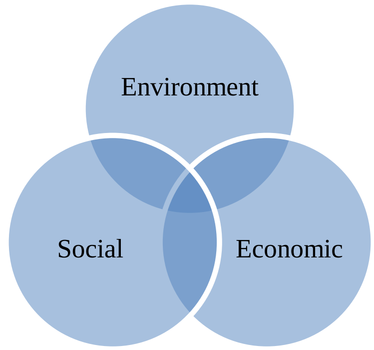


Figure 1.4 Triple Bottom Line (TBL) of sustainability (United Nations, 1987)

Green practices can be integrated into buildings at any stage, from design and construction, to renovation and deconstruction. To achieve the optimum benefits, sustainable methods need to be practiced at all lifecycle stages of buildings. The US EPA has provided a potential benefits list of green buildings, as shown in Table 1.1.

Table 1.1 Benefits of green buildings (US EPA, 2010b)

Environmental Benefits	Economic Benefits	Social Benefits
Enhance and protect biodiversity and ecosystems	Reduce operating costs	Enhance occupant comfort and health
Improve air and water quality	Create, expand, and shape markets for green product and services	Heighten aesthetic qualities
Reduce waste streams	Improve occupant productivity	Minimize strain on local infrastructure
Conserve and restore natural resources	Optimize life-cycle economic performance	Improve overall quality of life

United States Green Building Council (USGBC, 2011) data shows following benefits of green buildings over conventional buildings:

- 30% energy saving
- 30-50% water saving
- 35% reduction in carbon emission
- 50-90% reduction in construction waste
- 8-9% operating cost decrease

In the following sections environmental and socio-economic benefits of a typical green building are compared with a typical conventional building. Both buildings are three story commercial offices of same size located in Vancouver, British Columbia.

1.2.1 Environmental benefits

The comparative environmental impacts of conventional and green building types were investigated by a life-cycle assessment.. Figure 1.5 shows the major energy consumption of green and conventional buildings throughout their life span. Green building consumes less coal, natural gas, and crude oil over its life cycle. Energy consumption is reduced by more than 30% and therefore more resources are preserved by adopting green building approach. This point is significant since the building and construction industry accounts for 30-40% of all natural resource consumption globally. Consuming limited natural resources more 'efficiently', use of green material in construction of buildings, and shifting from fossil fuels to renewable energy resources benefit both present and future generations.

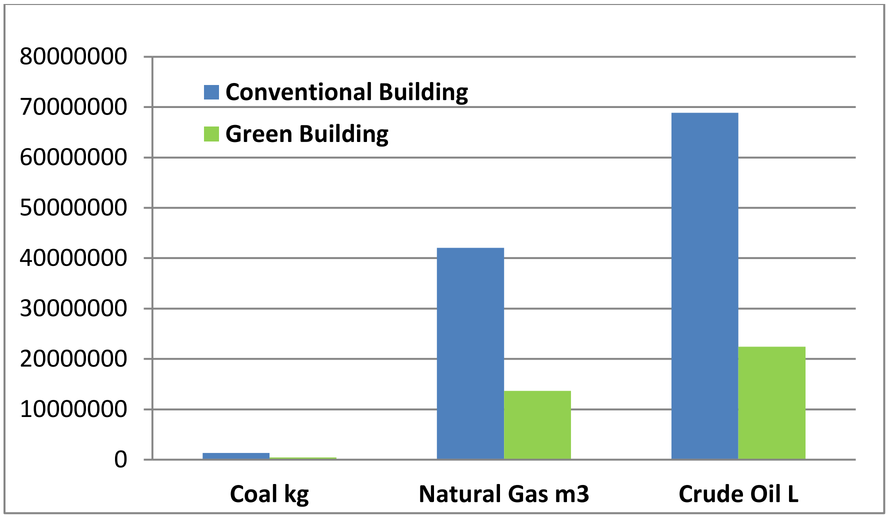


Figure 1.5 Energy consumption of green and conventional office building

Figure 1.6 illustrates the Carbon Dioxide (CO_2) emissions of both buildings. In addition to less resource consumption, the green building releases 33% less CO_2 to earth's atmosphere. This is a significant achievement at global scale, since building and construction are the biggest sector in global GHG emission (USGBC, 2007).

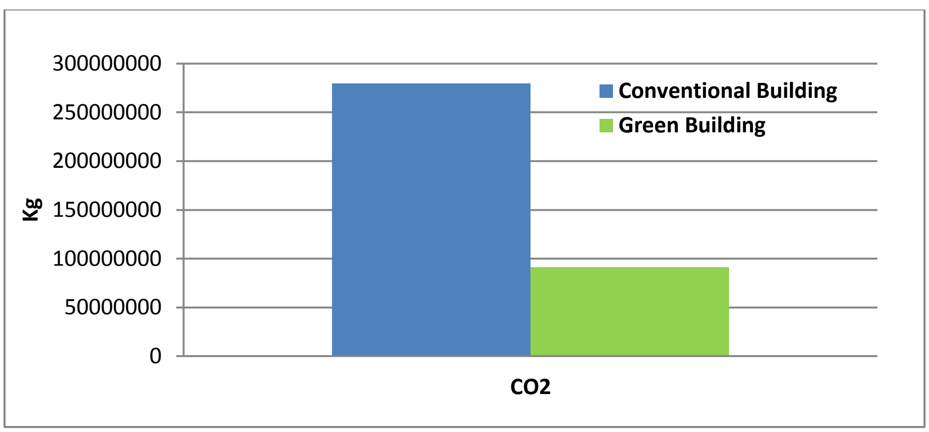


Figure 1.6 Life-cycle CO2 emission of green and conventional office building

Figure 1.7 shows release of major GHG and particulates in the air for both buildings. Particulates are tiny subdivisions of solid matter suspended in the air and can cause serious human health problems. Particulate matter pollution is estimated to cause 22,000-52,000 deaths per year in the United States and 200,000 deaths per year in Europe (Mokdad, 2004).

Sources of particulate matter can be man-made or natural. Green building produces 25-35% less GHG and particulate matters to the air. Considering that buildings are responsible for 30% of all GHG emissions (USGBC, 2007), green buildings benefits - society as a whole by their reduced emissions.

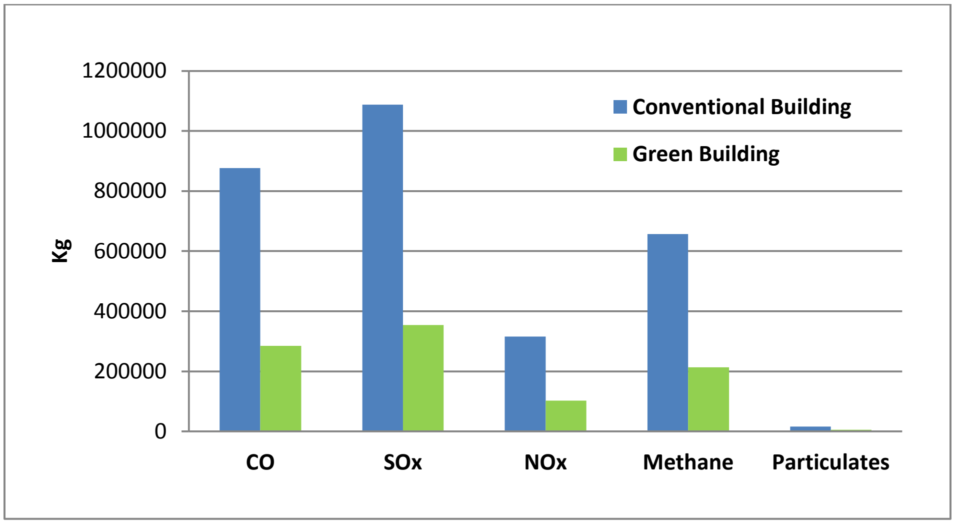


Figure 1.7 GHG emission of green and conventional office building

1.2.2 Socio-economic benefits

Economic analysis of buildings is performed through Life Cycle Cost/Benefit Analysis (LCCBA). In this study, LCCBA of a green building is compared with a conventional building considering complete life-span of the structures; from construction to demolition. Result shows that although green building requires 1-2% more capital cost for construction, overall lifecycle cost of the green building is reduced by 40-65%. Moreover, the payback period of shifting toward green building is one year. This is a significant positive point for both public and private sectors investments in green buildings.

Social benefits analysis covers a wide spectrum of criteria, ranging from beauty (aesthetics of building) to human health impact of buildings. Some of these criteria are very subjective and there is no clear evaluation system to assess them (e.g. beauty of buildings). Studies in the literature mainly focus on productivity increase and health benefits of green buildings compare to conventional buildings. Result of these analyses show that green building occupants have 1%-2% higher productivity that results in $600-$1000 annual saving per green building occupant (Kats, 2003). However, the assumptions made for calculation of productivity increase and generalizing it for all types of buildings (i.e. residential, commercial, industrial) is questionable.

1.3 Current building rating systems

There are various indicators applied to the building industry to evaluate its sustainability performance. Buildings are categorized as green if they meet sustainability criteria defined by the assessment tools/frameworks. The concept of sustainable buildings came into existence in early 1980s and the idea to develop rating systems to evaluate sustainability performance of buildings became popular in the early 1990s (Yudelson, 2008). Chew and Das (2007) provided a review of building rating systems since 1990 and discussed the "scope, limitation, and working principle" of current rating systems. The authors divided building-rating systems into three generations; i.e. (1) pass-fail, (2) simple additive, and (3) weighted additive systems.

- First Generation: Pass-Fail Systems: Most of the green building-grading systems in this category are prescriptive certification programs for conventional building design compared with the building codes, standards, or bylaws. These rating systems have limited focus on energy use of the building, type of material use, and indoor environmental quality.

- Second Generation: Simple Additive Systems: The rating systems in this category gained popularity mainly for their simplicity to follow. However, there is little scope for user modification to reflect regional differences or individual preferences; hence amendments are realized for such systems (ASMI, 2002).
- Third Generation: Weighed Additive Systems: for the rating systems in this category, determination of weightage mostly involves "judgmental or conscious-based values due to the inherent complexity and the lack of objective basis" (Chew and Das, 2007). Expert opinions are pursued to rank the parameters and then weightings are allocated by analyzing such data through various methods such as, analytic hierarchy process, statistical correlation and artificial neural networks.

Table 1.2 provides a summary of the major grading systems in the world. In the following sections the most widely used rating system of each category is reviewed. Also, the review of the newly developed rating system, the Living Building Challenge (LBC) is outlined. Section 1.3.5 provides a critical review of the current building rating systems. Figure 1.8 shows the registered logos for these rating systems.

Table 1.1.2 Major Building Grading Systems (Chew and Das, 2007)

Type	Year	Grading System	Country
First generation	1981	R-2000	Canada
	1989	P-mark	Sweden
	1997	ELO & EM scheme	Denmark
	2001	Energy Star	USA
Second generation	2000	Leadership in Energy and Environmental Design (LEED)	USA
Third generation	1990	Building Research Establishment Environmental Assessment Method (BREEAM)	UK
	1993	Building Environmental Performance Assessment Criteria (BEPAC)	Canada
	1996	Hong Kong Building Environmental Assessment Method (HK-BEAM)	Hong Kong
	2001	Housing Quality Assurance Law (HQAL)	Japan
	2002	Green Building Tool (GBTool)	International
	2002	Global Environmental Method (GEM)	UK
	2003	Green Star	Australia
	2004	Green Globes	USA
	2004	Go Green. Go Green Plus	Canada
	2004	Maintainability Scoring System (MSS)	Singapore
	2005	National Australian Built Environment Rating System (NABERS)	Australia

Figure 1.8 Building rating systems, from left to right: Energy Star, LEED, BREEAM, and the Living Building Challenge

1.3.1 Energy Star

Energy Star was developed by the US EPA and US Department of Energy (DOE). To receive the certification, new homes must meet the EPA guidelines and need to be at least 15% more energy efficient as per prescriptive and performance based criteria set by the 2006 International Energy Conservation Code (IECC). The main focus of the Energy Star is on energy conservation. Energy Star criteria cover effective insulation, high performance windows, tight construction and ducts, efficient heating or cooling equipment, and Energy Star approved lighting and appliances (ENERGYSTAR, 2006).

1.3.2 LEED

Leadership in Energy and Environmental Design (LEED) is a point-based building rating system developed by the United States Green Building Council (USGBC) in 2000. LEED covers various types of buildings, including, LEED for new construction and major renovation (NC), existing buildings (EB), commercial interior (CI), core and shell (CS), homes (H) and neighborhood development (ND).

LEED-NC (USGBC, 2009), has total of 110 points consisting of 100 base points, 6 possible points for innovation in Design and 4 regional priority points. A building may receive a particular level of certification based on its point scores. The certification levels are:

- Certified 40–49 points
- Silver 50–59 points
- Gold 60–79 points
- Platinum 80 points and above

Buildings are assessed in five categories for certification, namely:

- Sustainable sites

- Water efficiency
- Energy and atmosphere
- Materials and resources
- Indoor environmental quality (IEQ)

LEED is the most widely used rating system in North America.

1.3.3 BREEAM

BREEAM was created by Building Research Establishment (BRE) of the United Kingdom in 1990. Since its inception, more than 200,000 building have received BREEAM certification, making the BREEAM the world's foremost environmental assessment method and rating system for buildings (BREEAM, 2012). BREEAM is applicable to residential houses, industrial buildings, offices and schools. There are nine assessment categories with predefined weightings that are evaluated, as shown in Figure 1.9.

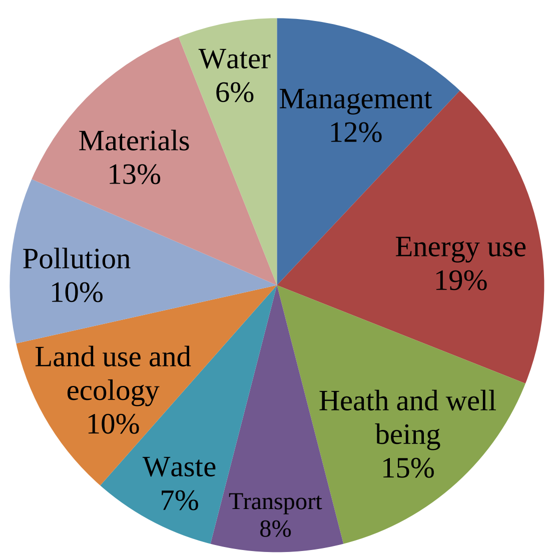


Figure 1.9 BREEAM evaluation categories

Each category has sub-categories allocated with pre-weighed points that are either cumulative or otherwise, depending on performance against certain specified standards such as SAP 2005. The credits are added up to a final overall score, rated on following scale:

- Pass: 30%
- Good: 45%
- Very good: 55%
- Excellent: 70%
- Outstanding: 85%

1.3.4 The living building challenge

Developed by the International Living Building Institute (ILBI) in 2006, The Living Building Challenge (LBC) is a philosophy, advocacy tool and certification program that addresses development at all scales. It is comprised of seven performance areas (petals): Site, Water, Energy, Health, Materials, Equity and Beauty. These are subdivided into a total of twenty Imperatives, each of which focuses on a specific sphere of influence (ILBI, 2012). Imperatives spectrum is very wide, ranging from net zero water and energy to democracy and social justice.

To receive LBC certification, a building must meet all imperatives assigned to a typology (i.e. renovation, building, landscape + infrastructure, and neighborhood). Also, LBC certification is based on actual rather than model performance of the building. These two points distinguish LBC from other rating systems such as LEED or BREEAM.

1.3.5 Critique of current building rating systems

Among all of building sustainability rating systems, LEED is the current leading system in the North America (including Canada), mainly due to its ease of use.

Although LEED is the most common building rating system, it has many weaknesses in measuring true sustainability performance of the built environment. The main problem with point-based grading systems is 'point hunting', where a building can achieve required points for certification, without addressing critical points of energy efficiency and resource preservation. Moreover, points are lost for credits that are outside the scope of certain projects (Chew and Das, 2007).

Newsham et al. (2009) studied 100 LEED-certified buildings for their energy consumption and discovered that 28-35% of LEED-certified buildings actually use more energy than conventional buildings. Hossaini and Hewage (2012) conducted a LCA study on Rapidly Renewable Materials (RRM) suggested by LEED and concluded that these materials should not be selected without considering the location of construction.

Also, major rating systems (including LEED) do not disclose the reasoning behind the scores associated to each credit. These frameworks are mainly designed based on conscious or expert opinions (Fowler and Rauch, 2006) rather than analysis of building performance/ effect on the environment, economy, and society.

The current scope of the leading building sustainability assessment systems in North America is limited to the construction phase (for LEED-NC) or construction and a short period of post-construction phase (for LBC). These building rating system such as LEED, take a snap shot of building lifecycle (usually completion point of construction phase) and evaluate the building based on its condition/performance at that point. However, based on the green building definitions, the building needs to be evaluated for its entire life-cycle impact. In addition, the main focus of current leading rating systems is on the environmental aspect of sustainability with low or no consideration on socio-economic aspects.

Due to the above pointed weaknesses in current sustainability rating systems, the construction industry needs a more comprehensive method that covers lifecycle of building materials which provides a better estimation of building's environmental impact. The suggestion outlined in this research thesis is an emergy-based sustainability rating system that is localized for Canadian building industry: i.e. Em-Green sustainability rating system. The framework developed for Em-green sustainability rating system can be adopted for other nations and can be expanded to develop a global sustainability measure for the built environment. In order to use this framework for other nations, first emergy evaluation of that nation needs to be evaluated using emergy accounting for regional studies (Discussed in Chapter 4). Also, emergy database of major construction materials in that nation needs to be created, as described in Chapter 3.

1.4 Introduction to emergy analysis

There is evidence that all energy transformations can be arranged in an ordered series to form an energy hierarchy (Odum, 1996). For instance, many joules of sunlight are required to make one joule of fuel, several joules of fuel is needed to make a joule of electricity, many joules of electricity is required to support information processing in a university, and so forth. Because different kinds of energy are not equal in contribution, work is made comparable by expressing each in units of one form of energy previously required (Odum et al., 2000). This quantity is *Emergy* (spelled with an "m") (Odum, 1986, 1988).

Emergy evaluation is an environmental accounting technique that creates an energy system for the thermodynamics of an open system (Odum and Odum 1981; Odum 1996). Odum (1996) proposed the concept of ‘energy hierarchy’ as an energy law. In any hierarchy, many units at one level contribute to a few units at the level above them. According to the second law of thermodynamics, any energy transformation consumes many calories of available energy, of one kind, to generate fewer calories of available energy of another kind. Therefore, an energy transformation works as a process that converts one or more kinds of available energy into a different type of available energy (Brown et al., 2004). By definition, emergy is the available energy of one kind that has been used up directly and indirectly to make a product or service (Odum, 1971, 1983, 1996).

Emergy uses the thermodynamic basis of all forms of energy and materials, but converts them into equivalents of one form of energy (Pulselli et al., 2008). Emergy assessment considers systems as a network of energy fluxes. It assigns a value to natural and economic products and services by converting them into equivalents of one form of energy, with reference to the theory of energy hierarchy in systems ecology (Pulselli et al., 2007a). The most common method is transforming all resources, including energy and matter, to solar energy (called solar emergy joule, solar emjoule or ‘sej’) since solar energy is the earth’s largest but most dispersed energy input (Brown and Ulgiati, 2004). For example, sunlight, fuel, electricity, and human service can be put on a common basis by expressing them all in the emjoules of solar energy that is required for each.

Emergy is also referred to as the “memory of energy” (Scienceman 1987). When a system is evaluated in solar emergy, the quantities represented are the 'memory' of the solar energy used to make it. Thus, the quantities are not energy and do not behave like energy (Brown and Herendeen, 1996). The emergy of different products is calculated by multiplying mass (g) or energy quantities (J) by transformity, which is a transformation coefficient. Transformity is one example of a unit emergy value and is defined as the emergy per unit energy. Transformity is the solar emergy required, directly or indirectly, to make one joule or one gram of a product or service. In other words, transformity is the emergy input per unit of product or service (Odum, 1971, 1983, 1996).

By definition, the solar emergy B_k of the flow k coming from a given process is:

$$B_k = \sum_i Tr_i E_i \qquad i = 1,2,\ldots,n \qquad \text{(eq. 1)}$$

where, E_i is the actual energy content of the i^{th} independent input flow to the process and Tr_i is the solar transformity of the i^{th} input flow (Pulselli et al., 2007). It is common to measure solar transformity in solar emergy joules per joule of product (sej/J) with a base that 1 emjoule is equivalent to 1 J of solar energy and transformity of solar energy is 1 sej/J (Ulgiati et al., 1995). The solar transformity of the sunlight absorbed by the earth is 1.0 by definition. Solar transformities represent the position of any product or service in the hierarchical network of the earth's biosphere (Odum, 1996). For instance, if 6,000 solar emjoules are required to generate 30 J of natural gasoline, then the solar transformity of that gasoline is 200 solar emjoules/J (6,000/30 sej/J). Transformities increase from left to right in the energy hierarchy diagrams, as shown in Figure 1.10. Solar energy is the largest but most dispersed energy input to the earth. The higher the transformity of an item, the more available energy of another kind is required to make it (Brown et al., 2004). For convenience, it is very common to use transformity values derived from other studies. It is assumed that transformity values are still valid under minor different conditions such as place and/or time (Meillaud et al., 2005). Moreover, most products have a range of transformities depending on their production process (Pulselli et al., 2008). In the literature, emergy values and transformities are reported in scientific form (e.g. 5.28E+12 sej/kg). For ease of use, emergy values can be reported using metric prefix of ‘tera’(10^{12}). For example, 5.28E+12 sej/kg can be written as 5.28 tera sej/kg.

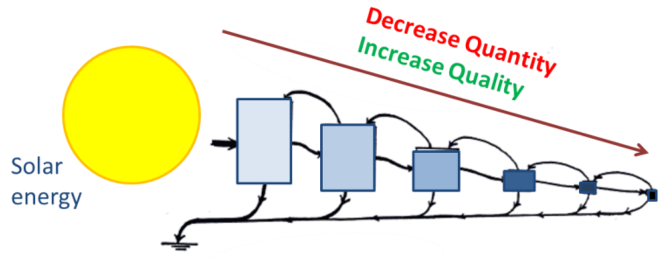


Figure 1.10 Energy hierarchy (Odum, 1996)

1.4.1 Comparison of system-evaluation methods: emergy, exergy and embodied energy

There are many techniques to analyze a system, among which exergy, emergy, and embodied energy are used widely.

As defined, emergy is the available energy of one kind that has been used up directly and indirectly to make a product or service. Exergy of a system is the maximum useful work possible during a process. Embodied energy is defined as the total energy (including fossil fuels, solar, nuclear, etc.) that was used in the work to make any product, bring it to market and dispose.

Among the system-evaluation methods, emergy was chosen for the analysis presented in this thesis because of its ability to normalize all products and services into a single unit. Emergy concept overcomes use of variety of units to quantify different inputs including materials, energy, and human services (Tilley & Swank, 2003).

The main use of exergy is for energy conversion systems, such as power plants where the major input is fossil fuels and major outputs are electricity or thermal power. Compare to emergy, exergy does not account for "goods and services in the market, or information required" for a system (Meillaud et al., 2005). Detailed comparison of emergy and exergy is available in the literature by Ulgiati (2000).

As per definition, embodied energy does not consider other inputs used to make a product or service such as material, human work and information. Detailed comparison of emergy and embodied energy is performed by Brown and Herendeen (1996).

1.5 Use of the emergy concept in building and construction industry

In this section, literature is reviewed for emergy studies related to building and construction industry. There are only a few studies reported in the literature, as summarized in the following paragraphs.

In reference to buildings, Pulselli et al. (2007b) performed an emergy analysis to evaluate a typical residential/commercial building in central Italy during its construction, maintenance and use phases. The authors used emergy analysis as a form of sustainability indicator, while common building evaluation methods, such as LEED, follow state-pressure environmental indicators.

In this study, building materials, technologies, and structural elements have been measured and compared to each other in order to evaluate their impacts. The following emergy-based indicators were developed for the building under study:

- Building emergy per volume (em- building volume)
- Building emergy/money ratio (em-building/money ratio)
- Building emergy per person (building inhabitant)

The authors' key finding from this analysis is that durability of material (life time) is an essential element of sustainability, since a longer building life span corresponds to lower annual emergy inflow for the building manufacturing stage. The authors indicated that the results of their study can be used as a basis for future evaluations in the field of the building industry.

In another study, Meillaud et al. (2005) applied emergy analysis to evaluate the Solar Energy Laboratory (LESO) building on the campus of the Swiss Federal Institute of Technology of Lausanne in Switzerland. The authors chose emergy since it accounts for both economical and information flows in addition to conventional environmental flows. The results of the analysis were expressed in three forms of unit emergy values: transformity, specific emergy, and emergy per unit money.

The evaluation established that a student leaving the LESO building has a transformity (emergy per unit energy) equal to 2.4E8 sej/J, which is about three times higher than the one which he/she had upon arrival, representing the knowledge gained through conferences and interactions with other students and professors.

Considering only energy and materials inputs, electricity was established to be the largest input to the system (2.7E+16 sej/year). The total emergy of the material inflows was determined to equal 1.7E+16 sej/year, paper being the largest material input (5.7E+15 sej/year). Also, the specific emergy (per mass) of some common building materials was also evaluated and compared to NRE (non-renewable energy). The authors' major conclusion was that information has the highest emergy inputs to the building, followed by human services and operating energies.

In another study, Brown and Buranakam (2003) performed emergy analysis to evaluate the life cycles of major building materials as well as the emergy inputs to waste disposal and recycle systems. The results show that, emergy per mass for building materials varies from a low 0.88 E9 sej/g for wood to a high of 12.53 E9 sej/g for aluminum. Generally, emergy per mass is a good indicator of recyclability, where materials with high emergy per mass are more recyclable.

In this paper, two types of solid waste disposal systems were evaluated using emergy methodology: municipal solid wastes (MSW), and construction and demolition wastes (C&D). Also, three different recycle trajectories were identified and analyzed:

- Material recycle, where it is used again as the same material
- By-product use, where a by-product from some process is used to make something entirely different
- Adaptive reuse, where a material after recycle is reused for an entirely different purpose

The authors developed three recycle indices measuring the benefits of various recycle systems and concluded that materials that have large refining costs have greatest potential for recyclability.

Another version of this paper was published as a thesis dissertation by Buranakam (1998) in the University of Florida, titled "evaluation of recycling and reuse of building materials using the emergy analysis method."

1.6 Research objectives

The objective of this research is to develop an emergy-based sustainability rating system for buildings in Canada, named the "Em-Green sustainability rating system".

The proposed sustainability evaluation system has the following characteristics:

- It is a user-friendly framework for building and construction industry in Canada
- It is based on the emergy methodology
- It covers the complete life-cycle of buildings (cradle-to-cradle), including resource extraction, manufacturing, transportation, construction, operation, maintenance and demolition (landfill or recycle).

- It includes the Triple Bottom Line (TBL) of sustainability- i.e.: environmental, social, and economical. For environmental aspects, lifecycle environmental impact is considered. Lifecycle cost analysis is performed for the economic assessment. Social assessment is limited to lifecycle impacts of buildings on human health.

To achieve the main objective of this research (i.e. development of the Em-green sustainability rating system for buildings in Canada), the following sub-objectives have been completed:

- Developed an emergy database for major construction materials in Canada
- Developed an Emergy accounting database for Canada and its provinces that includes emergy indices, indicators and maps of Canada and its provinces.
- Developed a user-friendly building assessment tool to assist decision making (i.e. decision support tool).

2 Chapter: Methodology

In this chapter, the methodology used to develop the emergy based sustainability rating system is discussed. Figure 2.1 illustrates the research methodology outline for development of the Em-green sustainability rating system. Each step is discussed in following sections.

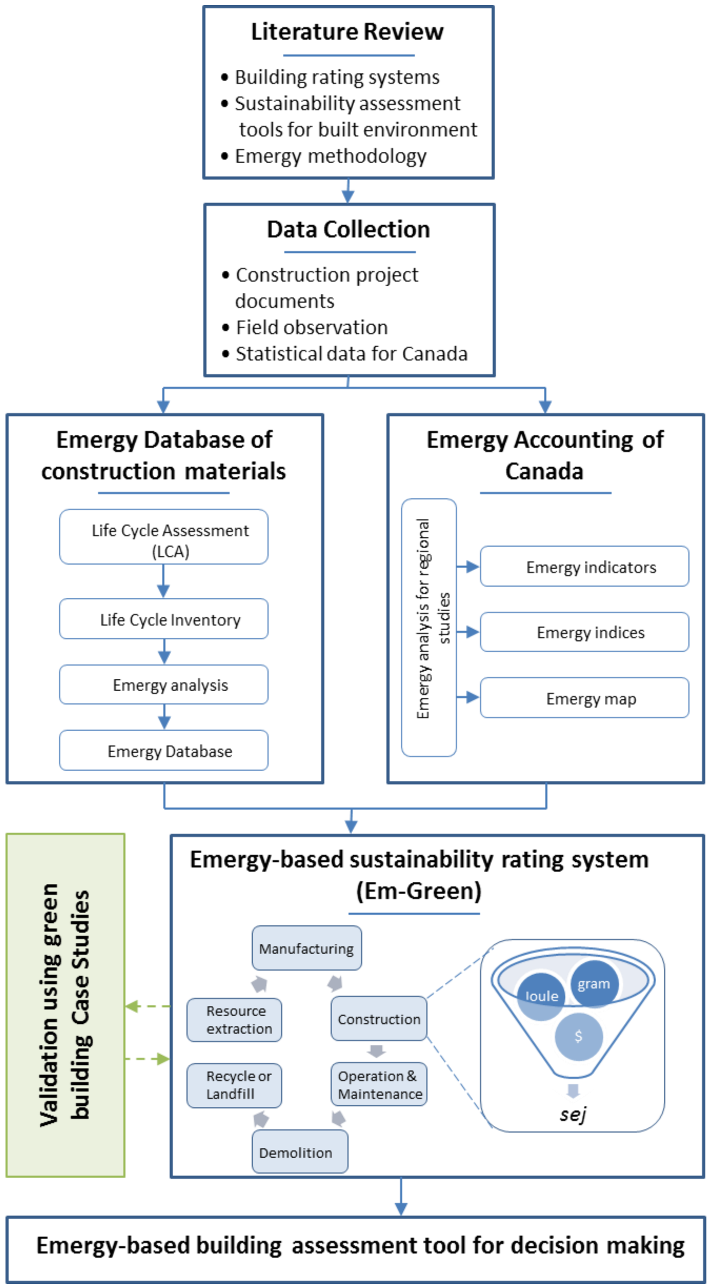


Figure 2.1 Research methodology outline

2.1 Literature Review and Data collection

Initially, a comprehensive literature review of building rating systems, sustainability assessment tools for the built environment, and emergy methodology was conducted and objectives of the research were defined accordingly. Building assessment tools were analyzed for their scope, strength, and limitations. In parallel, emergy methodology was explored and studies with a focus on building, housing and construction were investigated.

Based on the literature review and objectives of the research, necessary data was collected from various sources. These data were gathered from construction project documents, field observation and reliable Canadian statistical data. In addition, necessary tools to perform Life Cycle Assessment (LCA) were acquired.

2.2 Emergy Database of major construction materials in Canada

To develop an emergy-based sustainability rating system, it was first necessary to create an emergy database for major constructional materials in Canada. Athena impact estimator 4.1 and SimaPro 7.1 software were used to perform LCA for major construction materials and structural systems in Canada. Athena impact estimator 4.1 is a popular tool in North America that is designed to evaluate buildings and assemblies based on LCA. It is capable of modeling 95% of the building stock in North America, using the best available data (Athena Institute, 2011). LCA provides quantity and quality of all materials and energy forms that have been used in extraction, manufacturing and transportation of construction materials. It also evaluates environmental impacts associated with these stages.

Having raw quantities, emergy analysis was performed to calculate specific emergy (sej/g) of each construction material and assemblies using transformity values in the literature. An emergy calculation was performed for major construction materials in the Canadian construction industry and an emergy database is created, as discussed in Chapter 3.

2.3 Emergy accounting of Canada

To develop an emergy-based sustainability rating system, it was essential to perform emergy accounting for Canada and its provinces to get emergy indices, indicators, and emergy map. The most important index for this research is the emergy to money ratio (Em$) of Canada and its provinces to evaluate the socio-economic impact of construction projects (i.e. convert the $ values into sej). Em$ is the ratio of total emergy to the GDP of a nation (U/GDP). Emergy evaluation of socio-economic aspects of construction in Canada is discussed in Chapter 4.

2.4 Emergy-based (Em-green) sustainability rating system

Figure 2.2 shows the energy system diagram for the Em-green building rating system. The system diagram consists of major flows contributing at different stages of building lifecycle, which are resource extraction, manufacturing of materials, construction, operation, and maintenance and demolition (cradle-to-grave). Considered flows have different forms of energy, material (natural resources), human work, machinery, money, and transportation. The dashed-line shows the recycle scenario at the end of a building lifecycle. Flows of money in the system are illustrated as dashed lines with a $ sign. The energy system diagram is drawn based on the symbols of the energy systems language given by H.T. Odum (1971, 1983, 1996).

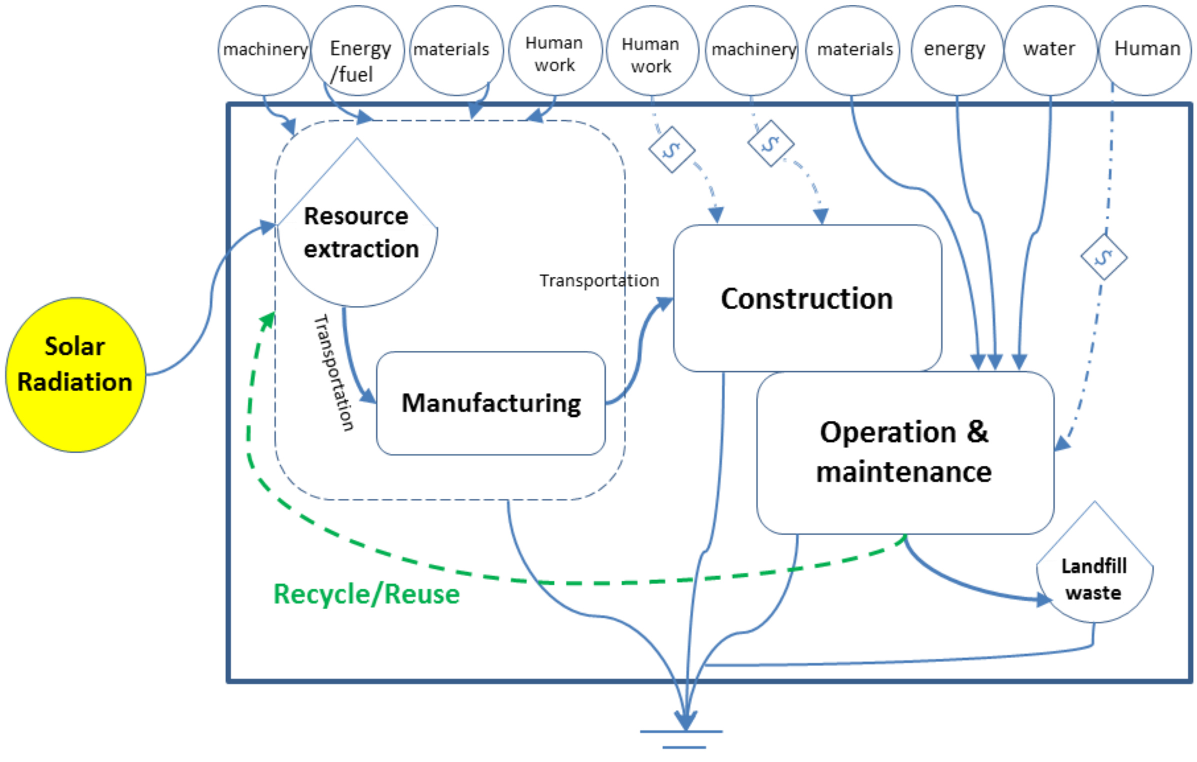


Figure 2.2 System diagram of Em-green building rating system

The impact of buildings on the environment, economy, and society is not limited to the construction phase. A comprehensive building rating system should cover all life stages of a building for sustainability assessment. Current leading rating systems in Canada do not sufficiently cover the complete life cycle of buildings. As illustrated in Figure 2.2, the complete lifecycle of buildings from cradle to cradle/grave is covered in the analysis. In the Em-green sustainability rating system, fluxes in each stage of a building lifecycle were transformed into their emergy equivalent and considered in sustainability assessment. Each stage is described in following subsections:

2.4.1 Resource extraction and material manufacturing stages

As described in section 2.2, an emergy database for major construction materials in Canada was created. It covers resource extraction and manufacturing stages in a lifecycle of a building. Also, SimaPro 7.1 was used to perform lifecycle assessment for transportation of construction materials to the construction site. The result of LCA is transformed to emergy values using transformity functions from the literature and emergy per unit of traveled distance (sej/km) was calculated.

2.4.2 Construction

Construction is a major phase of building or assembling the structure that includes tasks from different disciplines, including management, engineering, construction, machinery, and materials. Beside flows of material, energy, and transportation to the system, human work is a major flux in construction projects.

Human work done by engineering, management, and construction teams are measured by dollar value in the construction industry. These dollar values were transformed to emergy, using emergy/money ratio (i.e. Em$) of Canada. Hossaini and Hewage (2012) calculated Em$ value for Canada and all ten provinces based on current data.

2.4.3 Operation and Maintenance (O&M)

Post-construction phases in sustainability assessment are insufficiently considered in current major building rating systems in Canada. The main focus of the point-based building grading systems is on construction and material use, while building operation and maintenance is the longest stage of a building lifecycle and has the highest interaction with the occupants.

In the Em-green sustainability rating system, the impact of buildings on the health of occupants over life span of the building was considered as an important factor of social sustainability. In addition, operation energy from both non-renewable and renewable sources used for building operation, electricity generation, heating and cooling were captured in the assessment framework. Also, water consumption over the life-span of building for different purposes such as washing, toilet, and irrigation is included in the building rating system. Productivity increase and the health benefits of green buildings for occupants were measured based on time and money saved compared to conventional buildings. For example, a 1% increase in productivity is equal to about 5 minutes per working-day, equal to \$600 to \$700 per employee per year, or \$3/ft^2 per year (Kats, 2003). Dollar values were converted to emergy using the corresponding Em\$ ratio for Canada.

LCA was performed for various energy types used in Canadian buildings, including electricity, natural gas, oil, wood, propane, and other fossil fuels. The results of material and energy consumptions were transformed to emergy via transformity functions in the literature (Sej/J). The analysis was performed based on the building's life-span.

2.4.4 Demolition of building and recycle/disposal (end of life scenarios)

The evaluation of emergy used in demolition, recycle and disposal is based on Brown and Buranakam (2003). Emergy per unit of area (Sej/m^2) of demolition, recycling, and landfilling was calculated for the building and considered in the analysis.

Based on the emergy values calculated from each stage of the building lifecycle, total emergy and emergy per unit area (Sej/m^2) were calculated for the building under study. The building's sustainability was assessed by comparing its sej/m^2 to the three different sustainability levels of the Em-Green sustainability rating system. These three levels of sustainability need to be defined by performing emergy evaluation on a number of buildings across Canada to define the base building.

2.5 Emergy-based building assessment tool for decision making

A user-friendly emergy-based decision support tool for construction projects was developed based on Em-green sustainability rating system. This decision support tool provides the design team, construction manager or the project owner (as users) the ability to perform a sustainability comparison of different options available in each stage of a building lifecycle using emergy methodology.

2.6 Research deliverables

Following are the deliverables of this research study:

- An emergy database for major Canadian construction materials and structural systems.
- Emergy accounting of Canada and its provinces by calculating emergy indicators, indices and emergy maps for the region.
- An emergy-based building rating system that covers the triple bottom lines of sustainability: the Em-Green sustainability rating system
- A user-friendly building assessment tool based on the emergy database and the developed rating system (decision support tool).

3 Chapter: Emergy Database of Major Construction Materials in Canada

To develop the emergy-based sustainability rating system, first it is necessary to create an emergy database for major construction materials in Canada. According to the definition of emergy, emergy analysis requires the history of resources consumed to make that product or service. In this study, Life Cycle Assessment (LCA) technique was used to quantify the type and quantity of resources used in the lifecycle of each construction material, from cradle (resource extraction) to grave (end-of-life). LCA helps to develop an inventory of relevant energy and material inputs and environmental releases for each construction material. According to the ISO 14040 standards (2006), a life cycle assessment was carried out in four distinct phases, as shown in Figure 3.1.

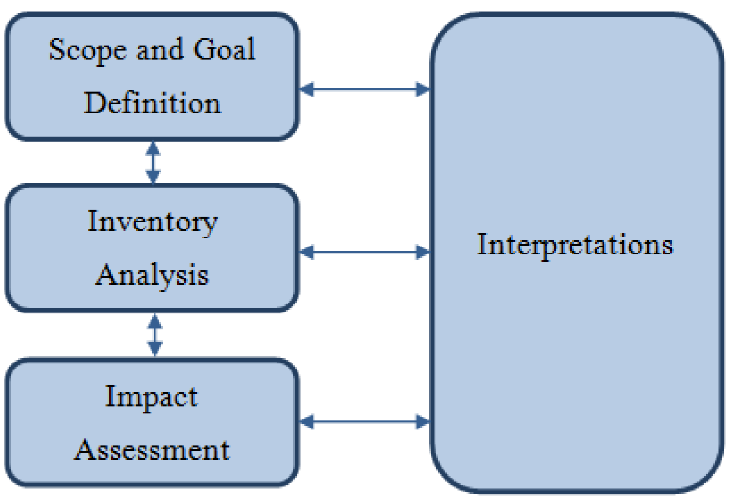


Figure 3.1 LCA Phases

Athena impact estimator 4.1, developed by the Athena Sustainable Materials Institute in Canada, was used to perform LCA for major construction materials in Canada (for inventory analysis and impact assessment). Athena impact estimator 4.1 is a popular tool in North America that is designed to evaluate buildings and assemblies based on LCA. It is capable of modeling 95% of the building stock in North America, using the best available data (Athena Institute, 2011). Among all LCA tools, such as SimaPro, GaBi and Athena, Athena was chosen as the main Life Cycle Inventory (LCI) for this study since:

- It is capable of modelling 95% of structural materials used in the Canadian construction industry based on current data.
- Unlike GaBi and SimaPro that are European-based, Athena uses a Canadian-based inventory. Therefore, the practices for manufacturing materials, transportation and maintenance are adjusted for Canadian construction industry, geography and climate.

However, the Athena impact estimator does not allow user to add or edit the materials. For LCA of construction materials that are not available in Athena database (mainly the green construction materials as discussed in section 3.1.1), SimaPro 7.1 was used and data were adjusted for Canadian environment.

In this analysis, environmental impact and resource consumption in developing construction materials in the following stage are included:

- Material manufacturing, including resource extraction and recycled content
- Related transportation
- On-site construction
- Maintenance and replacement effects

Various end-of-life scenarios was considered for each material, as discussed in Chapter 5.

3.1 Emergy database of construction materials

Following steps were performed to analyze and calculate the specific emergy of major construction materials in Canada. Figure 3.2 illustrates the methodology of creating the emergy database for Canadian construction materials.

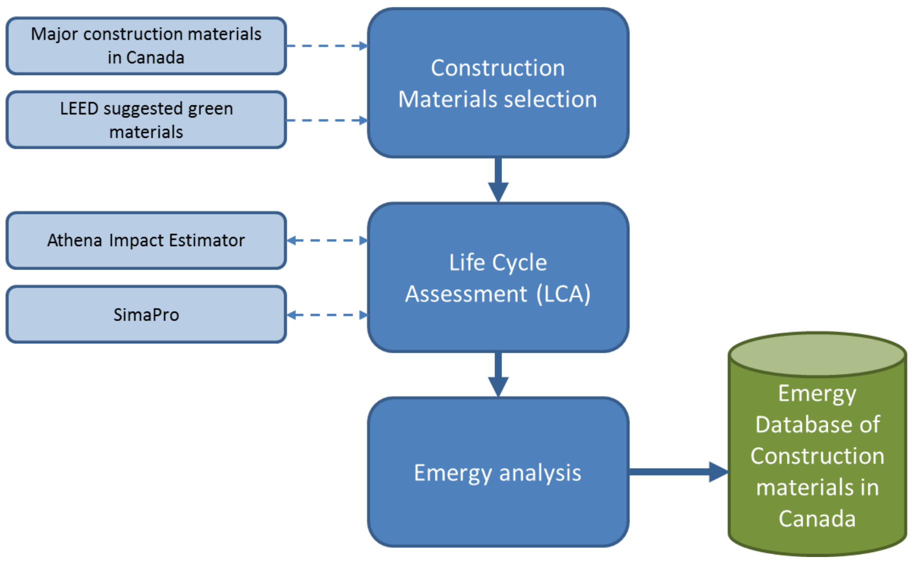


Figure 3.2 Methodology for developing the emergy database for construction materials

3.1.1 Material Selection

Construction materials chosen for this study are divided in two categories: major construction materials in Canada and green building materials.

3.1.1.1 Major construction materials in Canada

The major construction materials in Canada were chosen from the Athena Impact estimator inventory for analysis. Emergy assessment of these materials was then conducted.

3.1.1.2 Green building materials

LEED for new construction and major renovations suggested a list of ‘rapidly renewable materials’ (under MR Credit 6) for use in green buildings. The main intention of using these materials is to reduce the use and depletion of finite raw materials and long-cycle renewable materials (USGBC, 2009). Suggested rapidly renewable materials by LEED are bamboo, linoleum, wool, cotton insulation, agri-fiber, wheat board, strawboard, and cork. Among these materials, bamboo and linoleum were selected for emergy analysis of this study since they are gaining popularity for replacement of conventional flooring and structural materials in North America.

3.1.1.2.1 Bamboo

Bamboo (as shown in Figure 3.3) is a fast growing renewable material that can be used as a sustainable alternative for traditional structural materials, such as concrete, steel and wood (Van der Lugt et al., 2005). Strength, durability and rapid growth rate of bamboo makes it an 'environmentally friendlier' alternative compared to conventional structural materials. Bamboo is a very strong natural material that has twice the compressive strength of concrete and almost the same strength to weight ratio of steel in tension (Kubba, 2010).

Figure 3.3 Bamboo as a structural material (Bamboo Technologies, 2011)

3.1.1.2.2 Linoleum

Linoleum (Figure 3.4) is a natural material that is mainly used for flooring. Linoleum has many advantages over other flooring materials, such as flexible vinyl flooring and tiles, recyclable at the end of its life cycle, more durable and much lower Volatile Organic Compound (VOC) emissions (Kubba, 2010).

Figure 3.4 Linoleum as a flooring material (Peaceful Resources, 2011)

3.1.2 Life Cycle Assessment (LCA)

After selecting the materials, LCA for all the selected materials was conducted using Athena impact estimator and SimaPro. Resources include all types of material and energy consumptions in different lifecycle stages of selected construction materials. Initial LCA for green materials, that are not available in Athena and SimaPro database, were found from literature. This includes initial LCA of High Volume Fly Ash (HVFA) concrete by Chen et al. (2010), Linoleum by Jonsson et al. (1996), and Bamboo by Vogtländer et al. (2010). Athena's databases are regionally sensitive, taking into consideration manufacturing technology, transportation and electricity grid differences as well as recycled content differences for products produced in various regions. Athena databases are built from the ground up using actual mill or engineered process models and are not reliant on trade or government data sources. Appendix C the shows list of construction materials supported by Athena databases and the vintage of these databases.

3.1.3 Emergy analysis

Emergy analysis for each construction material was performed considering three major inputs: material, energy and transportation based on LCA outputs using transformity values available in the literature. Emergy Unit Values (EUV) (Transformity) used in the analysis are shown in Table 3.1.

Table 3.1 Emergy Unit Values (EUV) (Transformity) used in the study (Baseline: 9.44E+24 sej/yr)

	Item	Transformity	Unit	Source
Energy	Electricity	1.60E+05	sej/J	Romanelli (2000)
	Hydro	1.65E+05	sej/J	Odum (1996)
	Coal	4.00E+04	sej/J	Odum (1996)
	Diesel	6.60E+04	sej/J	Odum (1996)
	Heavy fuel oil	5.54E+04	sej/J	Bastianoni et al (2005)
	LPG	4.00E+04	sej/J	Bastianoni et al (2005)
	Natural Gas	4.80E+04	sej/J	Odum (1996)
	Gasoline	6.60E+04	sej/J	Odum (1996)
	Wood fuel	4.40E+04	sej/J	Odum (1996)
Material	Limestone	1.00E+09	sej/g	Odum (1996)
	Clay	2.00E+09	sej/g	Odum (1996)
	Iron Ore	8.55E+08	sej/g	Odum (1996)
	Sand	1.00E+09	sej/g	Odum (1996)
	Ash	3.80E+08	sej/g	Burankam (1998)
	gypsum	1.00E+09	sej/g	Odum (1996)
	Coarse Aggregate	1.00E+09	sej/g	Odum (1992)
	Fine Aggregate	1.00E+09	sej/g	Odum (1992)
	Water	1.25E+06	sej/g	Bastianoni and Marchettini (1995)
	Coal	1.40E+10	sej/g	Odum (1996)
	Natural Gas	3.11E+09	sej/g	Bastianoni et al (2009)
	Crude oil	2.01E+09	sej/g	Odum (1996)
	Wood	4.04E+08	sej/g	Bastianoni et al (2001)
	Steel	1.78E+09	sej/g	Odum (1996)

3.2 Results

Specific emergy values for construction materials were calculated using emergy transformity functions. Results are divided into two sections: emergy for the material use and energy consumption. Table 3.2 shows the sample emergy calculation for energy consumption performed for asphalt roofing material. Sample emergy calculation of resource use for concrete block is shown in Table 3.3. Transportation distances associated with each lifecycle stage is calculated based on Athena Impact estimator's lifecycle inventory.

Table 3.4 shows the emergy database created for major construction materials in Canada.

Table 3.2 Emergy calculation for asphalt roofing (energy consumption)

Energy Consumption	**Manufacturing**		**Construction**		**Maintenance**		**Total**			
	Material	Transportation	Material	Transportation	Material	Transportation		Unit Conv to Joule	Transformity (Sej/J)	sej
Electricity kWh	2.83E-02	0.00E+00	0.00E+00	0.00E+00	4.24E-02	0.00E+00	7.07E-02	2.55E+05	1.60E+05	4.07E+10
Hydro MJ	1.07E-01	7.60E-08	0.00E+00	2.73E-06	1.61E-01	9.68E-06	2.68E-01	2.68E+05	1.65E+05	4.42E+10
Coal MJ	1.02E-01	1.11E-06	0.00E+00	3.99E-05	1.53E-01	1.41E-04	2.56E-01	2.56E+05	4.00E+04	1.02E+10
Diesel MJ	2.43E-02	3.46E-04	0.00E+00	5.75E-03	3.65E-02	2.06E-02	8.76E-02	8.76E+04	6.60E+04	5.78E+09
Heavy Fuel Oil MJ	3.99E+00	3.67E-06	0.00E+00	1.32E-04	5.99E+00	4.67E-04	9.98E+00	9.98E+06	5.54E+04	5.53E+11
LPG MJ	4.08E-03	1.66E-07	0.00E+00	5.97E-06	6.12E-03	2.11E-05	1.02E-02	1.02E+04	4.00E+04	4.09E+08
Natural Gas MJ	6.89E-01	6.78E-06	0.00E+00	2.44E-04	1.03E+00	8.63E-04	1.72E+00	1.72E+06	4.80E+04	8.27E+10
Feedstock MJ	4.29E+00	0.00E+00	0.00E+00	0.00E+00	6.44E+00	0.00E+00	1.07E+01	1.07E+07	5.60E+04	6.01E+11
									(sej/kg)	**1.34E+12**

Table 3.3 Emergy calculation for concrete block (resource use)

Resource use	**Manufacturing**		**Construction**		**Maintenance**		**Total**		
	Material	Transportation	Material	Transportation	Material	Transportation		Transformity (Sej/J)	sej
Limestone kg	2.15E-03	0.00E+00	2.74E-03	0.00E+00	0.00E+00	0.00E+00	4.89E-03	1.00E+12	4.89E+09
Clay & Shale kg	6.88E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.88E-04	2.00E+12	1.38E+09
Iron Ore kg	5.51E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.51E-05	8.55E+11	4.71E+07
Sand kg	3.28E-04	0.00E+00	3.19E-04	0.00E+00	0.00E+00	0.00E+00	6.47E-04	1.00E+12	6.47E+08
Ash kg	1.84E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.84E-05	3.80E+11	6.98E+06
Gypsum kg	1.38E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.38E-07	1.00E+12	1.38E+05
Coarse Aggregate kg	4.95E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.95E-03	1.00E+12	4.95E+09
Fine Aggregate kg	1.16E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.16E-02	1.00E+12	1.16E+10
Water L	5.15E-04	0.00E+00	5.34E-03	0.00E+00	0.00E+00	0.00E+00	5.85E-03	1.25E+09	7.32E+06
Coal kg	1.57E-02	4.02E-07	1.83E-02	4.41E-05	0.00E+00	0.00E+00	3.40E-02	1.40E+13	4.76E+11
Natural Gas m3	4.15E-02	1.32E-06	3.19E-02	1.45E-04	0.00E+00	0.00E+00	7.35E-02	3.11E+12	2.29E+11
Crude Oil L	5.80E-03	8.10E-05	4.38E-03	3.47E-03	0.00E+00	0.00E+00	1.37E-02	2.01E+12	2.76E+10
								(sej/KG)	**7.56E+11**

Table 3.4 Emergy database created for major construction materials in Canada

Material	unit	Emergy or material use	Emergy of energy consumption	Total emergy
Portland cement Concrete	kg	1.17E+12	6.88E+11	**1.86E+12**
Concrete Block	kg	1.00E+12	2.38E+11	**1.24E+12**
Mortar	kg	6.37E+12	5.07E+11	**6.88E+12**
25% Fly Ash Concrete	kg	1.14E+12	3.26E+11	**1.47E+12**
High Volume Fly Ash Concrete	kg	8.10E+11	5.40E+11	**1.35E+12**
Cedar wood - cladding	kg	1.08E+12	1.56E+12	**2.64E+12**
Concrete break - cladding	kg	8.55E+12	8.01E+11	**9.35E+12**
Natural stone - cladding	kg	5.54E+12	3.74E+12	**9.28E+12**
Vinyl siding	kg	1.90E+12	1.19E+12	**3.08E+12**
Gypsum board	kg	3.91E+12	1.20E+12	**5.11E+12**
Fiberglass batt insulation	kg	1.85E+12	9.88E+11	**2.84E+12**
Polystyrene insulation	kg	9.74E+11	1.04E+12	**2.02E+12**
Organic felt roofing	kg	3.21E+12	1.62E+12	**4.83E+12**
Polyethylene roofing	kg	3.61E+12	3.83E+12	**7.45E+12**
EPDM membrane roofing	kg	2.92E+12	2.40E+12	**5.32E+12**
PVC membrane roofing	kg	2.61E+12	1.79E+12	**4.40E+12**
Asphalt roofing	kg	1.33E+12	1.34E+12	**2.67E+12**
ceramic tile	kg	2.69E+12	9.94E+11	**3.68E+12**
Aluminum	kg	6.24E+12	4.10E+12	**1.03E+13**
Solvent based alkyd paint	kg	5.53E+12	3.58E+12	**9.10E+12**
Standard glazing	kg	1.43E+12	9.64E+11	**2.39E+12**
Reinforcing rebar	kg	5.83E+12	2.50E+12	**8.33E+12**
Steel nails	kg	3.46E+12	1.96E+12	**5.42E+12**
Wide flange section (I) steel	kg	4.79E+12	2.24E+12	**7.03E+12**
Hollow structural steel section	kg	4.16E+12	1.90E+12	**6.05E+12**
Galvanized steel sheets	kg	4.30E+12	1.23E+12	**5.53E+12**
Softwood lumber	kg	2.64E+12	1.45E+12	**4.10E+12**
Plywood lumber	kg	2.96E+12	1.49E+12	**4.45E+12**
Glulam wood beam	kg	2.50E+12	1.60E+12	**4.10E+12**
Bamboo	kg	2.84E+12	1.53E+12	**4.37E+12**
Linoleum	kg	2.09E+12	6.95E+11	**2.78E+12**
Concrete footing - 200mm thick	$1m^2$	5.84E+14	3.79E+13	**6.22E+14**
Concrete block wall	$1m^2$	5.81E+14	7.48E+13	**6.56E+14**
Concrete tilt-up wall - 200mm thick	$1m^2$	6.04E+14	5.02E+13	**6.54E+14**
Wood Stud wall	$1m^2$	1.17E+13	6.71E+12	**1.84E+13**

3.3 Discussion

Result of analysis show that on average emergy of material use is responsible for 68% and emergy of energy consumption accounts for 32% of total emergy of the construction materials. Construction materials with the same structural purposes are analyzed in the following section.

3.3.1 Specific emergy of concrete

Concrete is used more than any other man-made material in the world (Lomborg, 2001) and the cement industry releases about 5% of the world CO_2 emissions (Pulselli et al., 2008). LEED does not suggest an alternative for Portland cement concrete currently used in the building industry. In this study, emergy analysis of High Volume Fly Ash (HVFA) concrete (commonly referred to as a “green” concrete) and 25% fly ash concrete is compared with Portland cement concrete to find the most sustainable option for the Canadian construction industry.

The specific emergy of Portland cement concrete was found as 1.86E+12 sej/kg. The emergy unit value for 25% fly ash concrete and HVFA concrete is 1.47E+12 sej/kg and 1.35E+12, respectively (Figure 3.5). This indicates that less energy and material is consumed in lifecycles of HVFA concrete. Therefore it has lower environmental impact and can be considered as a green alternative for Portland cement concrete.

Considering that fly ash is a byproduct of coal combustion, HVFA is more economical too. Usage of HVFA concrete in green buildings helps to reduce environmental footprint of a structure, since concrete is the most used construction material in Canada.

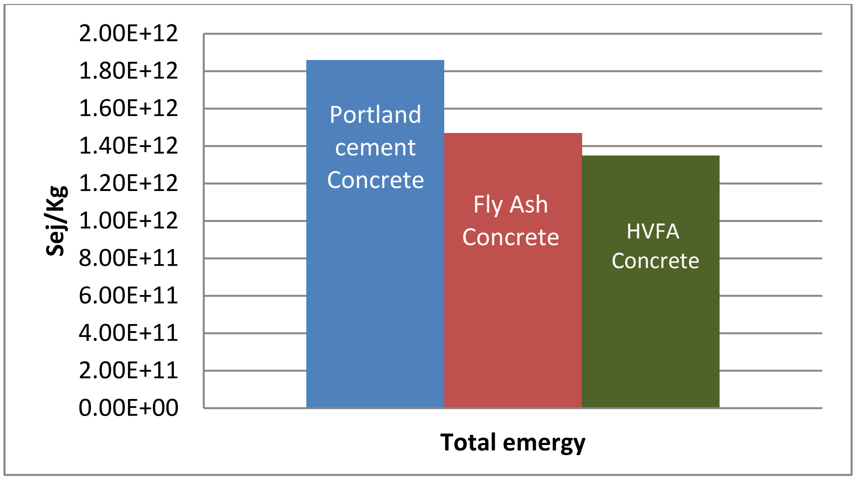


Figure 3.5 Specific emergy of different types of concrete

3.3.2 Tile and linoleum (flooring materials)

Flooring is an important part of construction. Since it covers large area of buildings, its contribution to buildings' overall environmental impact is significant. Currently, ceramic tiles are used as one of the main flooring material in building construction in Canada. Specific emergy of tile is calculated as 3.68E+12 sej/kg. LEED suggests linoleum, as a rapidly renewable material, for flooring. Comparing specific emergy of these two flooring materials show that linoleum with specific emergy of 2.78E+12 sej/kg is a sustainable option for flooring. Production of linoleum does not only require less natural, energy, and human resources, but also has lower environmental emission than ceramic tiles.

3.3.3 Plywood and bamboo (structural materials)

Plywood and bamboo can be used as load bearing materials in structural systems due to their high compressive strength. As per calculations, specific emergy of plywood and bamboo are 2.66E+12 sej/kg and 4.37E+12 sej/kg, respectively. Comparison of specific emergies of plywood and bamboo indicates that even though bamboo is one of the rapidly renewable materials suggested by LEED, it has almost twice the specific emergy of plywood. In other words, production of bamboo requires more environmental work than plywood, if used in the

Canadian construction industry. This is due to high emergy in transporting bamboo from either East Asia or South America to Canada. Transportation emergy for bamboo is 2.36E+12 sej/g, compare to 0.00919E+12 sej/g for plywood as a locally produced material in Canada.

The emergy analysis shows that the rapidly renewable materials suggested by LEED should not be chosen without considering their total cradle-to-grave environmental impacts. The main goal of LEED rating system is to classify sustainable structures. The case of bamboo indicated that LEED should categorize rapidly renewable materials according to the construction zone of final use, accounting for factors such as transport, and should not simply supply a general list.

3.3.4 Cladding materials

Cladding is the application of one material over another to provide a skin or layer intended to control the infiltration of weather elements, or for aesthetic purposes. Cladding materials are widely used in Canada. Emergy analysis shows that cedar wood (2.64E+12 sej/kg) is more sustainable compared to concrete break (9.35E+12 sej/kg) and natural stone (9.28E+12 sej/kg), as shown in Figure 3.6.

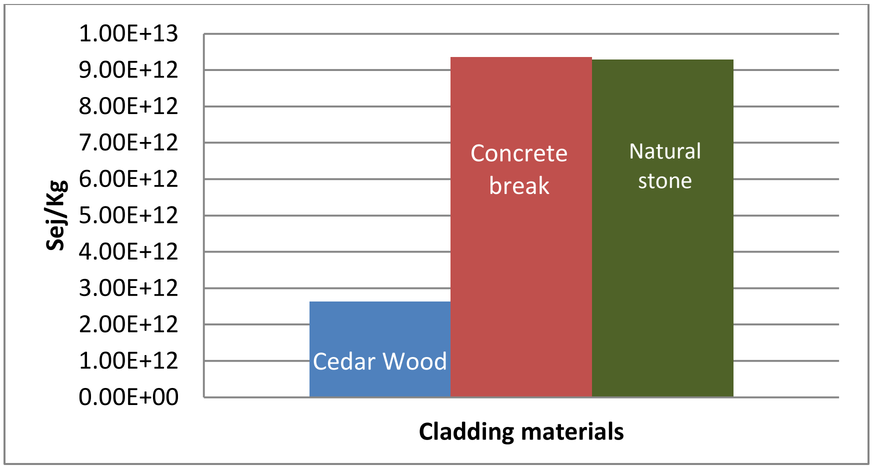


Figure 3.6 Specific emergy of cladding materials

3.3.5 Roofing materials

The typically cold climate of Canada escalates the importance of roofing materials. A building's roofing material provides a shelter from the natural elements such as rain and snow, and insulation against heat and cold. Emergy analysis shows that asphalt roofing with specific emergy of 2.67E+12 sej/kg is the most environmentally friendly option compared to other roofing materials commonly used in Canadian construction industry. Figure 3.7 illustrates the specific emergy of major roofing materials in Canada.

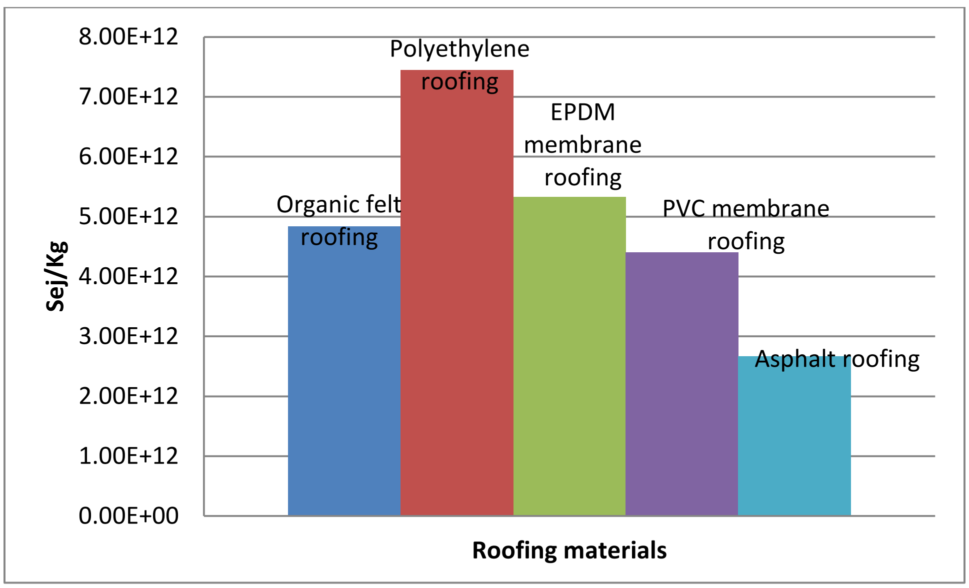


Figure 3.7 Specific emergy of roofing materials

4 Chapter: Emergy Analysis for Canada

Sustainable regional management (development) requires an understanding of interactions between social, economic, and ecological systems within the boundaries of a region. Combining information about type, location, and amount of resource consumption within a region is crucial for large-scale regional planning. Flow of resource fluxes to a region, including energy, matter, human activities, and money need to be quantified. Human–environment interactions in regions can be illustrated, showing that human activities use resources, the variable intensity of which creates spatial patterns (Pulselli et al., 2007).

To develop an emergy-based sustainability rating system for Canada, it is essential to perform a comprehensive emergy assessment of Canada and its provinces. The result of this analysis provides an emergy equivalent to money spent in Canada. In other words, the emergy to money ration (Em$) of Canada is calculated to convert dollar values of socio-economic aspects of construction to the emergy equivalents.

4.1 Overview

The aim of this chapter is to perform an emergy evaluation of Canada and the ten provinces: Alberta, British Columbia, Manitoba, New Brunswick, Newfoundland and Labrador, Nova Scotia, Ontario, Prince Edward Island, Quebec and Saskatchewan. An emergy evaluation of regions and their resources provides a large scale perspective for an assessment of environmental areas, and assists in informed decision making for the public benefit (Odum, 1996). Specifically, the objective of this chapter is to identify and quantify the main flows of energy, matter, and money that go in and out of the boundaries of Canada and its provinces. Other examples of emergy evaluations of states and nations can be found in the literature with reference to Odum and Odum (1983), Pillet and Odum (1984), Huang and Odum

(1991), Ulgiati et al. (1994), Campbell (1998), Ortega et al. (1999), Pulselli et al. (2001), Kang and Park (2002), Higgins (2003), Tilley and Swank (2003), Pulselli et al. (2004), Campbell et al. (2005), Pulselli et al. (2007), Pulselli et al. (2008), and Brown et al. (2009).

4.1.1 Flows considered in the analysis and the source of raw data

Emergy evaluations of energy resources, transformation processes, and regional systems involve calculation of all energy and material flows in and out of the system studied. This thesis follows the "standard" synthesis table that is provided as a template for the regional system evaluation based on an emergy evaluation of the United States, conducted by Stachetti (Emergy Systems, 2011a). The raw input data to the system (E_i) are gathered from the most recent data available in reliable databases, such as Statistics Canada, Natural Resources Canada, and the Food and Agricultural Organization (FAO) of the United Nations (UN). Figure 4.1 illustrates a synthetic description of the resource flows and transformation processes that occur within the system boundary. This diagram shows both the external relationships between the system and its outside sources as well as between its own parts (in the form of arrows that represent flows of energy, matter, and money). The energy system diagram is drawn based on the symbols of the energy systems language given by H.T. Odum (1971, 1983, 1996).

4.1.2 Energy system diagram

In the diagram shown in Fig. 4.1, the large rounded rectangle defines the boundaries of Canada, as the system under study. It covers different flows, including matter and energy that contribute to the emergy system. It also demonstrates the circulation of money in the system and shows the gross domestic product of Canada. Resources are categorized based on their origin that is either from outside the system, such as environmental inputs and purchased energy and goods or within the system. Also, sources are classified as either renewable or non-renewable.

Environmental resource inputs and renewable resources (R) such as sun, rain, and wind enter the system from the left. Non-renewable resources that are created within the system boundaries are (N_0, N_1 and N_2). (N_0) represents rural resources, such as soil and forest biomass, if their storage consumption rate is more than their regeneration. (N_1) designates the reserves of fuels and minerals that are renewed over longer periods of geologic time. Export pathway (N_2) shows flow of resources that pass through the system without significant transformation. Examples include minerals that are mined and exported abroad without further processing. Imports to the system are shown on the top and right of Figure 4.1. Imports include the emergy of fuels and minerals (F), goods (G), and the total imported service emergy (P_2I) that is the product of the dollars of imports (I) and the average emergy/money ratio (P_2) of the world. The flow of money is shown with a dashed-line and ($) in the system diagram. The exports to the markets on the lower right have pathways for fuels, goods, and services similar to those discussed for imports. Emergy of goods (B) and emergy of non-renewable exports (N_2) include emergy of services required in their process and delivery. In Figure 4.1, money received from exports in the markets on the right is represented by dashed lines that add up to the total dollars received for exports (E) that flow into Canada's Gross Domestic Product (GDP). The total emergy of services exported is the product of the exports expressed in dollars (E) times the average emergy/$ ratio of the world (P_1E).

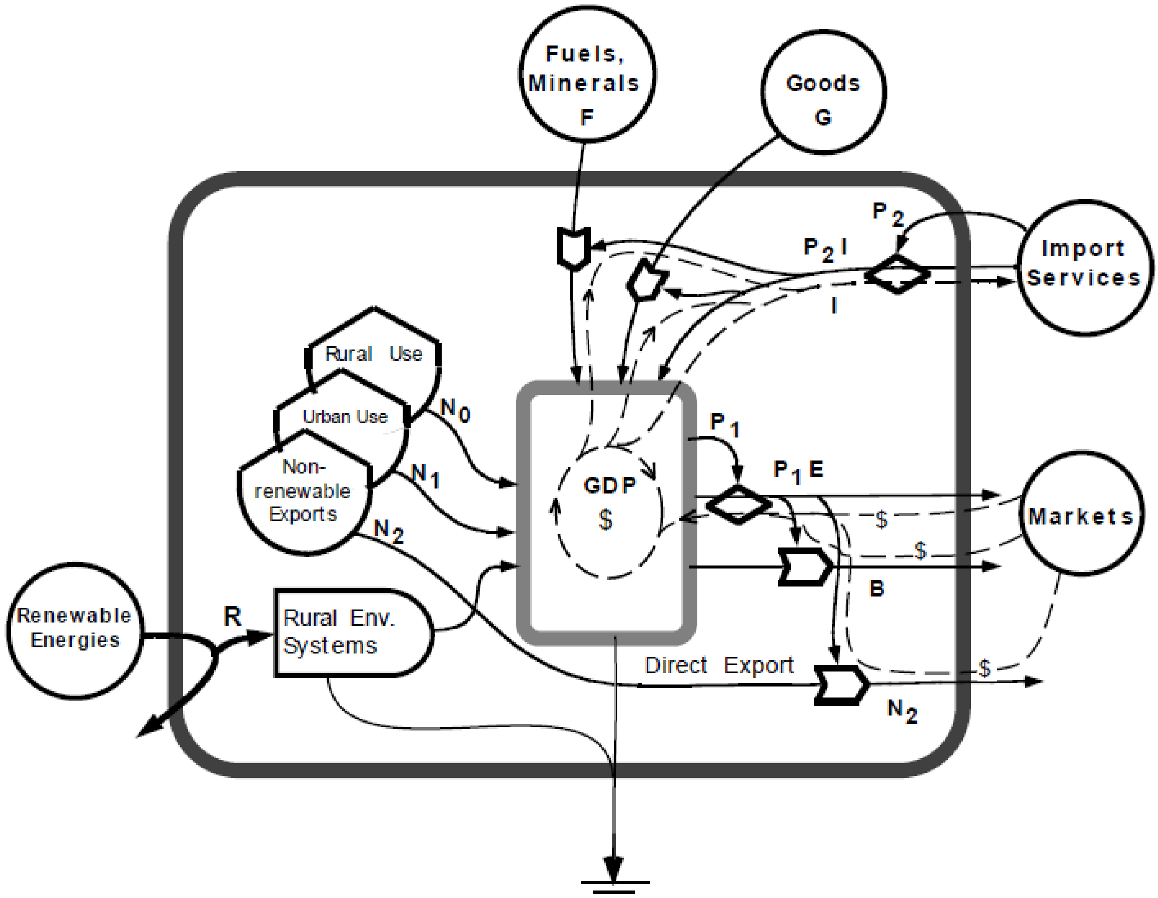


Figure 4.1 Energy System diagram of Canada (Adopted from generic system diagram for country by M.T. Brown, available online at Emergy Systems, 2011b)

4.1.3 Source of transformities and outcomes of the study

Emergy calculation is performed based on the transformities from the corresponding references: (a) (Odum et al., 2000), (b) (Odum, 1996), (c) (Brown and McClanahan, 1996), (d) (Romitelli, 2000), (e) (Brown and Bardi, 2001), (f) (Brown and Brandt-Wiliams, 2000), (g) (Odum and Arding, 1991), (h) (Luchi and Ulgiati, 2000) and (i) this study. Transformities are relative to the 15.83E+24sej/yr planetary emergy baseline. Values are reported in scientific format (for example, 2.50E3 means 2.5 x 10^3 that is same as 2500).

The following performance indicators were calculated for Canada and all the provinces:

- Emergy Yield Ratio (EYR) is the total emergy used divided by total emergy invested. EYR is a measure of how much an investment pushes a process to exploit local resources and enhances its contribution to the economy. In other words, EYR reflects the ability of a certain system to provide energy to the economy by magnifying its investment. The higher the EYR value, the lower the system's dependence on economic investment.
- Environmental Loading Ratio (ELR) is the ratio of nonrenewable (N) and imported emergy (EI) use to renewable emergy use (R), ((N+EI)/R).
- Emergy Investment ratio (EIR) is the ratio of purchased inputs to local resources (L), both renewable and non-renewable (EI/L).
- Emergy Sustainability Index (ESI) is the ratio of the EYR to the ELR. It measures the contribution of a resource or process to the economy per unit of environmental loading. To be sustainable, a process or system must obtain the highest yield ratio (EYR) at the lowest environmental loading (ELR) (Ulgiati and Brown, 1998).
- Emergy density (ED) is the ratio of total emergy to the area of the system (U/area).
- Emergy per Person (EpP) is the ratio of total emergy to the population (U/population).
- Emergy money ratio (Em$) is the ratio of total emergy to the GDP of a nation (U/GDP).

In addition to performance indicators, emergy maps of Canada as a function of quantities (in terms of emjoules) and locations (in terms of provinces) are generated to show intensities of emergy values across Canada. Pulselli et al. (2007, 2008) created emergy geography of the provinces of Siena and Cagliari in Italy in order to locate areas where resource flows achieve the lowest, medium, and highest emergy intensities. In this paper, an emergy calculation is performed for all ten provinces of Canada and the results are presented in maps, showing the total emergy consumption, emergy per person, and emergy density within the boundaries of Canada.

4.2 Results and discussion

The result of this analysis is divided in two sections: 4.2.1 outlines the analysis outcome for Canada and 4.2.2 discusses the result of the provinces.

4.2.1 Canada

In this section, a synthetic report including some of the final results for the emergy accounting of Canada is discussed. Based on the nature of the flow, each flow is categorized into one of the following groups: renewable resources, indigenous renewable energy, nonrenewable sources from within the system, imports and outside sources, and exports. Emergy value of each group is shown in Figure 4.2.

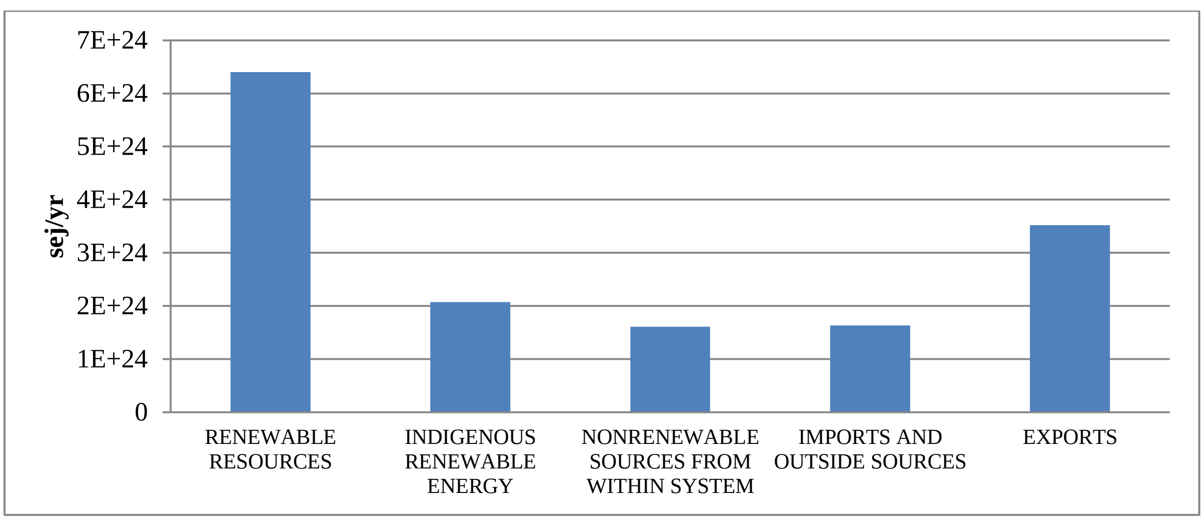


Figure 4.2 Emergy flow of Canada

Table 4.1 shows major emergy flows in Canada for a period of one year. It includes the quantities of resources consumed with the corresponding transformity and equivalent amount of emergy flows for each resource.

Table 4.1 Emergy flow of Canada

No.	Item	Raw data	Unit	Transformity (sej/unit)	Ref.	Solar Emergy (sej/yr)
Renewable resources:						
1	Sunlight	3.70E+22	J/yr	1.00E+00	a	3.70E+22
2	Rain, chemical	3.85E+19	J/yr	3.05E+04	a	1.17E+24
3	Rain, geopotential	1.34E+19	J/yr	4.70E+04	a	6.32E+23
4	Wind, kinetic energy	2.56E+20	J/yr	2.45E+03	a	6.28E+23
5	Waves	4.26E+19	J/yr	5.10E+04	a	2.17E+24
6	Tide	1.24E+19	J/yr	7.39E+04	a	9.14E+23
7	Earth Cycle	1.45E+19	J/yr	5.80E+04	a	8.40E+23
Renewable energy:						
8	Hydroelectricity	1.65E+18	J/yr	3.36E+05	b	5.53E+23
9	Agriculture Production	1.20E+18	J/yr	3.36E+05	c	4.02E+23
10	Livestock Production	5.46E+16	J/yr	3.36E+06	c	1.84E+23
11	Fisheries Production	6.47E+14	J/yr	3.36E+06	c	2.17E+21
12	Forest Extraction	4.22E+19	J/yr	2.21E+04	d	9.33E+23
Nonrenewable sources from within system						
13	Natural Gas	6.24E+18	J/yr	5.88E+04	d	3.67E+23
14	Oil	5.45E+18	J/yr	8.90E+04	b	4.85E+23
15	Coal	1.36E+18	J/yr	6.69E+04	b	9.10E+22
16	Limestone and fertilizers	2.76E+13	g/yr	5.13E+09	b	1.42E+23
17	Metals	1.34E+12	g/yr	1.12E+09	b	1.50E+21
18	Soil losses	3.03E+14	g/yr	1.68E+09	b	5.08E+23
19	Topsoil losses	2.05E+17	J/yr	7.40E+04	e	1.52E+22
Imports and outside sources:						
20	Fuels	2.86E+18	J/yr	9.27E+04	b, d	2.65E+23
21	Metals	5.07E+12	g/yr	2.78E+09	b, f, g	1.41E+22
22	Minerals	1.30E+14	g/yr	1.68E+09	b	2.18E+23
23	Food & ag. products	7.24E+16	J/yr	3.36E+05	c	2.43E+22
24	Livestock, meat, fish	3.20E+15	J/yr	3.36E+06	c	1.08E+22
25	Chemicals	1.06E+13	g/yr	1.48E+10	g	1.57E+23
26	Finished materials	1.32E+10	g/yr	1.66E+12	f, h	2.19E+22
27	Mach.& trans equip.	3.69E+13	g/yr	6.70E+09	e	2.47E+23
28	Service in imports	4.04E+11	$/yr	1.66E+12	b	6.71E+23
Exports:						
29	Food & agriculture products	4.75E+17	J/yr	3.36E+05	c	1.60E+23
30	Livestock, meat, fish	8.91E+15	J/yr	3.36E+06	c	3.00E+22
31	Finished materials	4.86E+09	g/yr	1.66E+12	f, h	8.08E+21
32	Fuels	7.52E+18	J/yr	8.15E+04	d, b	6.13E+23
33	Metals	2.92E+13	g/yr	2.78E+09	b, f, g	8.14E+22
34	Minerals	3.13E+14	g/yr	1.00E+09	b, f	3.13E+23
35	Chemicals	2.85E+13	g/yr	1.48E+10	g	4.22E+23
36	Mach. & trans equip.	3.06E+13	g/yr	6.70E+09	e	2.05E+23
37	Service in exports	3.99E+11	$/yr	4.22E+12	i	1.69E+24

The main emergy flows for Canada is also quantified in the form of indices, as follows:

- The total emergy consumption in Canada (U) is 5.98E+24 sej. This value corresponds to the sum of all emergy flows that supply the region.
- The total renewable emergy (R) is 1.81E+24 sej. It is 30.3% of the total emergy flow in Canada.
- The total local renewable emergy (N) is 2.54E+24 sej that accounts for 42.5% of total emergy.
- The total imported emergy, or emergy investment (EI) as sum of all inflows to the region from exports is 1.63E+24 sej.

The emergy of renewable resources in Canada is very significant. It includes emergy flows from natural cycles including solar radiation, rain, wind, waves, tide, and the earth's cycle. The large land area of Canada and its long coast lines are the main reason for substantial emergy of its renewable resources. These flows have very low transformity values since they come directly from the environment.

In terms of emergy, Canada depends on external sources (imports) for 27% of the total domestic consumption. Around 73% of resources (both renewable and non-renewable) used in the country are locally available within the boundaries of the region. Native renewable resources that include hydroelectricity, agricultural production, livestock production, fisheries production and forest extraction provide more emergy to the system (2.1E+24 sej) than local nonrenewable sources (1.6E+24 sej) such as, natural gas, oil, coal and metals extractions.

4.2.2 Provinces

After sorting inputs into relevant categories, various indicators for the population and area were calculated. These indicators and indices were calculated for Canada and all ten provinces, as shown in Table 4.2. Figure 4.3 shows a graph with classes of aggregated emergy flows for the provinces of Canada (Pulselli et al., 2008).

Table 4.2 Emergy flows and indices in Canada and its provinces

Province	R	N	L	EI	U	Em$	ED	EpP	ELR	EIR	EYR	ESI
			R+N			U/GDP	U/area	U/pop	N+EI/R	EI/L	U/EI	EYR/ELR
	sej/yr	sej/yr	sej/yr	sej/yr	sej/yr		sej/km^2					
Alberta	1.10E+23	7.92E+23	9.02E+23	1.43E+23	1.05E+24	4.23E+12	1.63E+18	2.81E+17	8.50	0.16	7.35	0.86
British Columbia	1.69E+23	1.66E+23	3.35E+23	1.75E+23	5.10E+23	2.67E+12	5.51E+17	1.13E+17	2.02	0.52	2.91	1.44
Manitoba	9.74E+22	6.98E+22	1.67E+23	7.74E+22	2.45E+23	4.80E+12	4.42E+17	1.98E+17	1.51	0.46	3.17	2.09
New Brunswick	1.55E+22	1.63E+22	3.18E+22	8.56E+22	1.17E+23	4.27E+12	1.64E+18	1.56E+17	6.58	2.69	1.37	0.21
Newfoundland and Labrador	6.80E+22	1.01E+23	1.69E+23	3.68E+22	2.06E+23	8.23E+12	5.50E+17	4.04E+17	2.03	0.22	5.60	2.76
Nova Scotia	1.19E+22	2.02E+22	3.21E+22	6.11E+22	9.33E+22	2.72E+12	1.75E+18	9.85E+16	6.84	1.90	1.53	0.22
Ontario	1.61E+23	1.33E+23	2.94E+23	1.17E+24	1.47E+24	2.54E+12	1.60E+18	1.11E+17	8.11	3.99	1.25	0.15
Prince Edward Island	2.04E+21	2.94E+21	4.98E+21	7.72E+21	1.27E+22	2.67E+12	2.24E+18	8.97E+16	5.23	1.55	1.65	0.31
Quebec	2.44E+23	2.53E+23	4.97E+23	3.90E+23	8.87E+23	2.92E+12	6.50E+17	1.11E+17	2.64	0.79	2.27	0.86
Saskatchewan	1.02E+23	1.73E+23	2.75E+23	7.74E+22	3.52E+23	6.22E+12	5.95E+17	3.34E+17	2.45	0.28	4.55	1.85
Canada	**1.81E+24**	**2.54E+24**	**4.35E+24**	**1.63E+24**	**5.98E+24**	**4.22E+12**	**5.99E+17**	**1.73E+17**	**2.30**	**0.37**	**3.67**	**1.59**

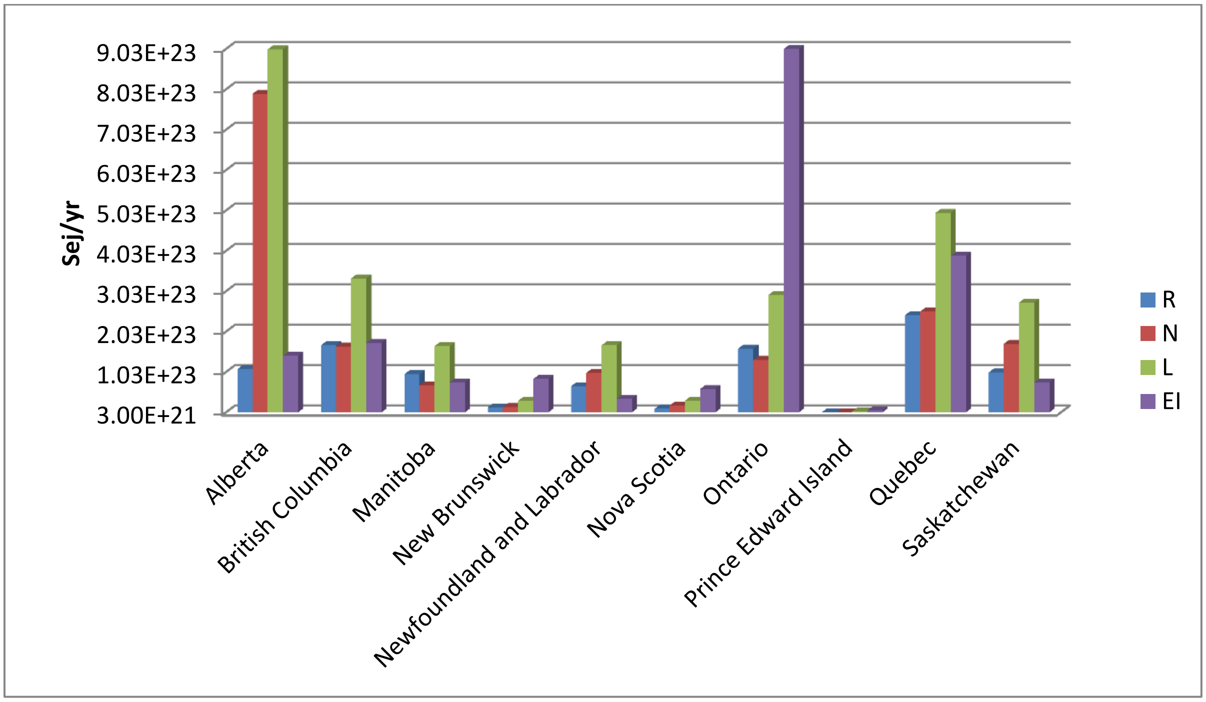


Figure 4.3 Emergy flow classified as Renewable (R), non-renewable (N), local (L), and total imports (EI) for the provinces of Canada

- Environmental Loading Ratio (ELR)

Canada has a very low level of ELR (= 2.30). This ratio indicates the existence of a firm equilibrium between the availability of natural renewable resources and the exploitation of non-renewable resources (such as fossil fuels). However, the ELR value for some of the industrialized provinces, such as Ontario (ELR = 8.11) and Alberta (ELR=8.5), is above the Canadian average due to their higher utilization of non-renewable resources. On the other hand, the ELR of Manitoba (1.51) and British Columbia (2.02) is low. These areas can be considered as locations of natural capital storage with very low impact in terms of resource use and extraction. Therefore, their importance to the sustainability of the country is very strategic.

- Emergy Sustainability Index (ESI)

As described, the ESI is the ratio of the EYR to the ELR. It measures the contribution of the regions to the economy per unit of environmental loading. It provides a multi-dimensional measure of the long term sustainability of a region. The higher this index, the more an economy relies on renewable energy sources. When related to economies, a low ESI (less than one) indicates a highly developed 'consumer' oriented economy while a high ESI (greater than ten) indicates an economy that has been termed 'undeveloped'. ESI ratios of between one and ten are referred to as 'developing economies' (Brown and Ulgiati, 1997). Canada and all provinces have ESI values of either less or close to one. These values indicate that Canada as a whole and all ten provinces developed 'consumer' oriented economies that highly relies on non-renewable energy resources (such as fossil fuels).

- Emergy per Person (EpP)

Emergy per person can be used as a measure of the potential average standard of living of a population. The EpP of Canada is 1.73E+17 sej/person. The EpP of provinces with active economies and high emergy resources such as Alberta (2.81E+17 sej/person) and Saskatchewan (3.34 E+17 sej/person) is higher than that of smaller provinces such as Prince Edward Island (8.97 E+17 sej/person) and Nova Scotia (9.85 E+17 sej/person).

- Emergy money ratio (Em$)

Em$ is the ratio of total emergy to the GDP of a nation (U/GDP). Em$ is an appropriate measure for evaluating an economy as it includes environment, information, human goods, and services. Developed countries like the United States and Japan have lower Em$ ratios than the less developed or developing countries, such as Liberia and Kenya. Less developed countries have more rural areas and use direct input from environment resources for their people (Odum, 1996).

Although Canada has one of the strongest economies in the world, Em$ of Canada is 4.22E+12 sej/$. Figure 4.4 shows the Em$ of Canada compared to that of other countries as reported by Cohen et al. (2006). The emergy money ratio of Canada is similar to that of Australia (4.8E+12 sej/$) as these two countries have very large land areas and relatively low populations - i.e. low population densities.

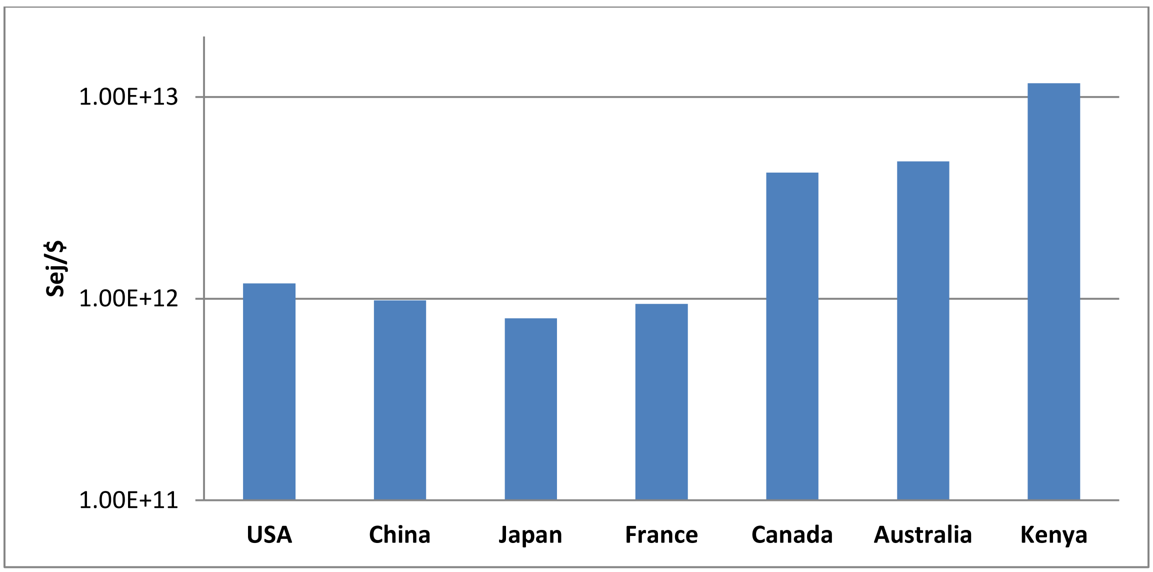


Figure 4.4 Emergy money ratio of Canada and other countries

- Total emergy use (U)

Figure 4.5 shows the emergy consumption share of each province. Ontario (30%), Alberta (21%) and Quebec (18%) are the biggest emergy consumers. On the other hand, Prince Edward Island (0.26%), Nova Scotia (2%) and New Brunswick (3%) use the least emergy of Canadian provinces.

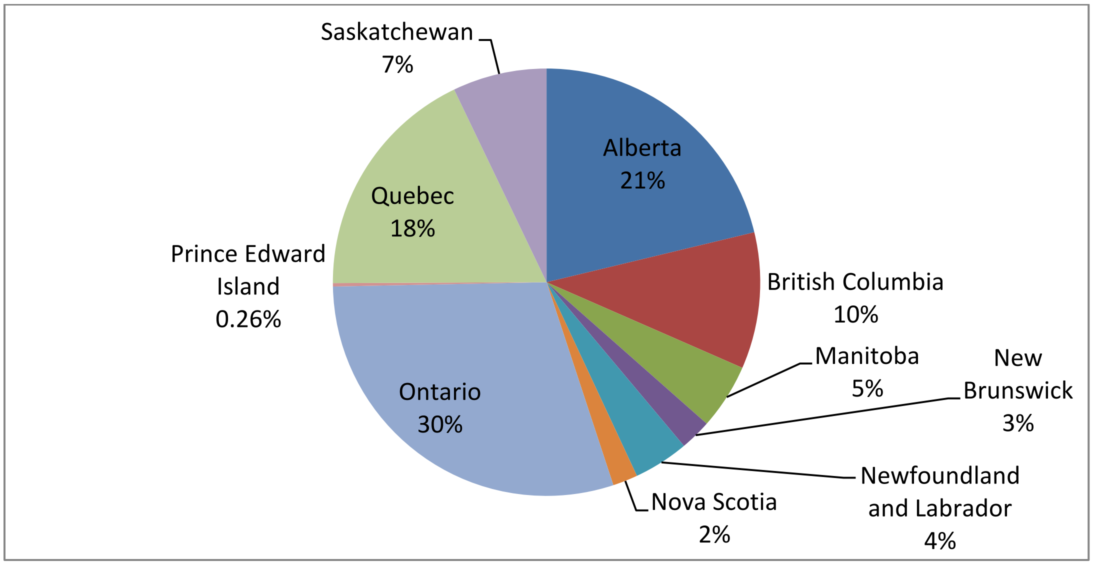


Figure 4.5 Total emergy flow (U) by provinces

- Emergy maps

Figures 4.6, 4.7 and 4.8 present the results in the form of gray scale emergy maps for Canada and its provinces. It is an emergy geography that illustrates resource consumption by two parameters: (1) the quantities consumed based on their environmental costs, and (2) the location of consumption. These maps show different performances of each province of Canada in terms of emergy fluxes. The accuracy of maps developed in this research study is at the provincial level, mainly due to unavailability of data for more detailed analysis of cities, and communities. It is assumed that the emergy indices shown on the map is representative of the province.

The map of total emergy used (U) in Canada is shown in Figure 4.6. Ontario (the darkest color) has the highest emergy consumption rate. Moving east from Ontario, consumption intensity decreases to a minimum (the lightest color) in the Prince Edward Island.

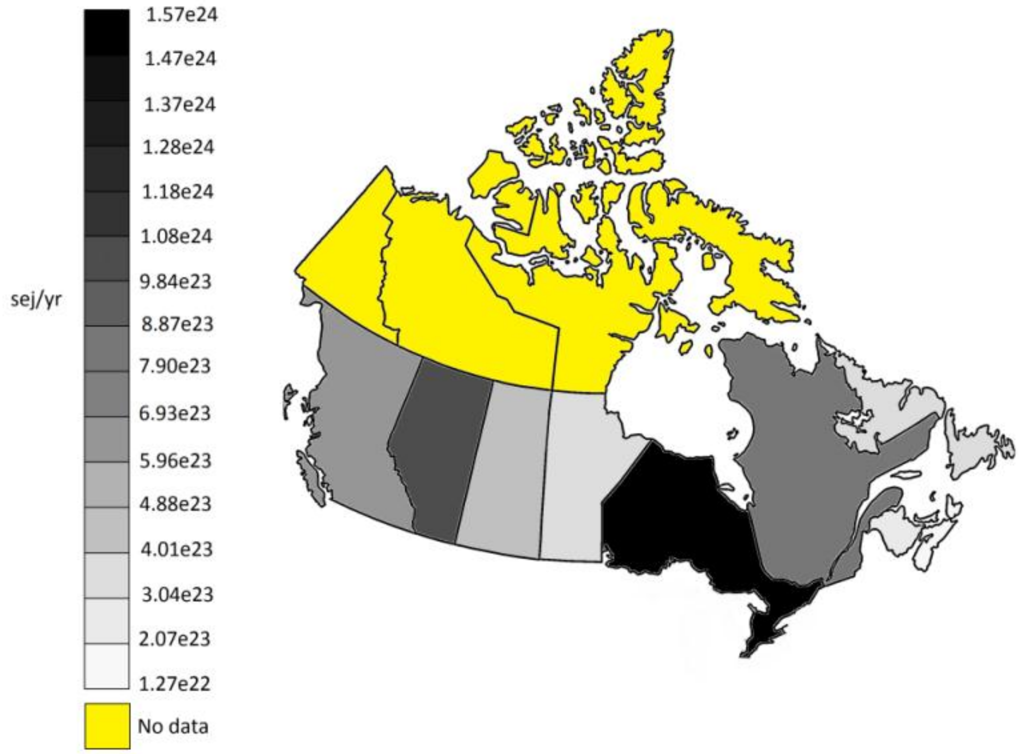


Figure 4.6 Total emergy (U) map of Canada

Figure 4.7 illustrates the emergy per person across Canada. Saskatchewan has the second highest (EpP) rate among the Canadian provinces. Moving west, (EpP) decreases in Alberta and British Columbia. Similar trend is seen when moving towards the east (from Saskatchewan) with the exception of Newfoundland and Labrador that has the highest (EpP) in Canada (4.04E+17 sej/person).

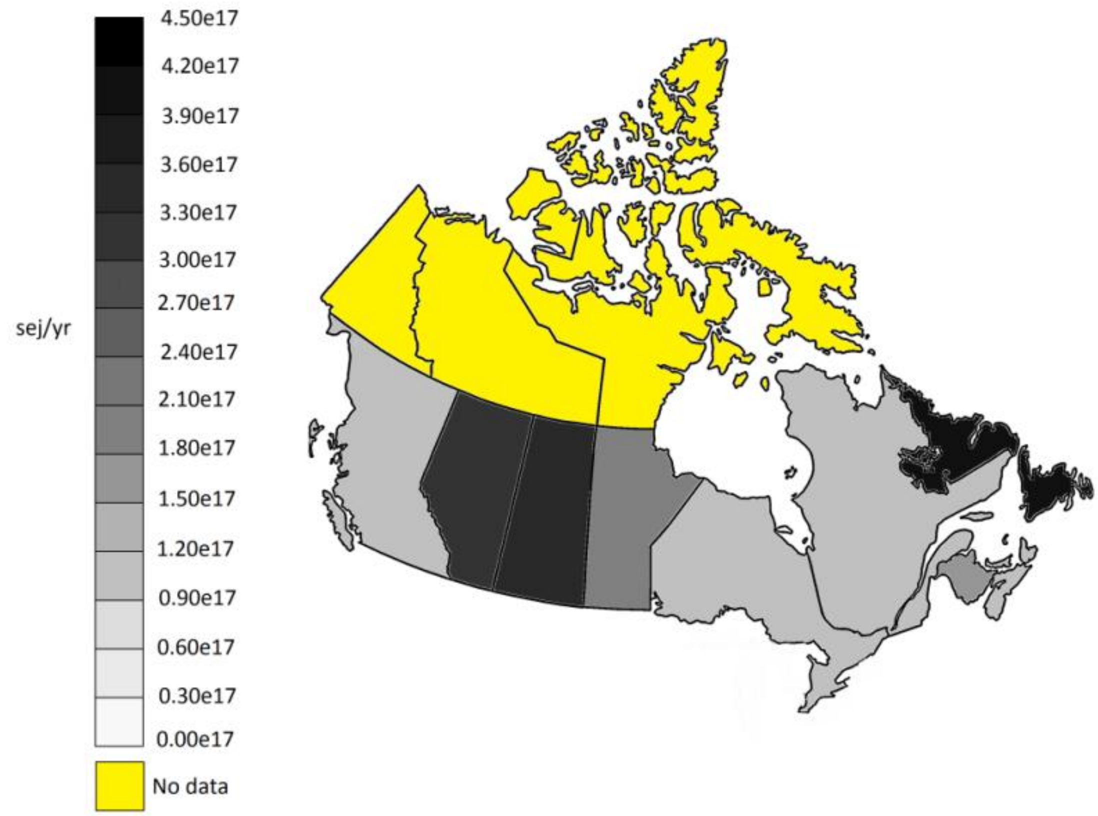


Figure 4.7 Emergy per person (EpP) map of Canada

As shown in Figure 4.8, Emergy Density (ED) as a function of total emergy consumption and land area does not follow any particular trend across Canada. ED in British Columbia, Manitoba and Newfoundland and Labrador is lower than in Alberta, Ontario and Nova Scotia.

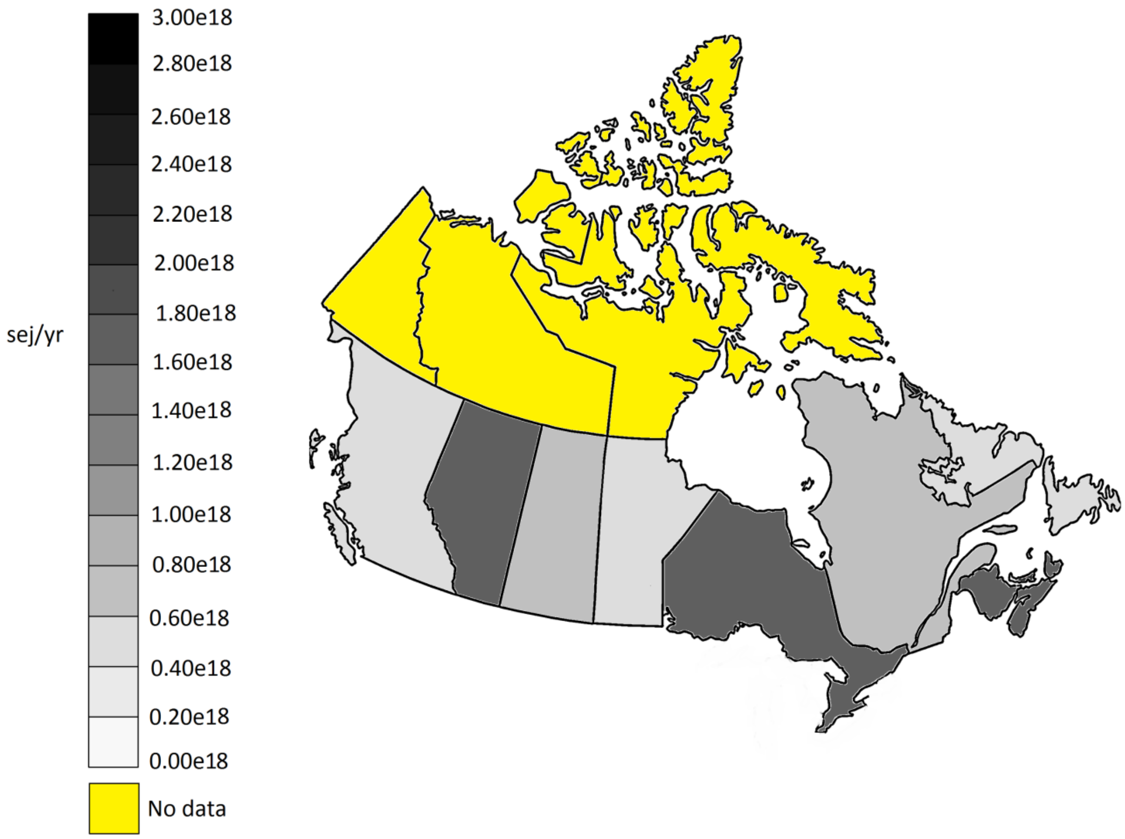


Figure 4.8 Emergy density (ED) map of Canada

In this chapter, emergy methodology is adopted for a large-scale regional study of Canada and its provinces. Major renewable and non-renewable resource fluxes to the system are quantified and converted to emergy form, using corresponding transformity functions. Emergy accounting of Canada is estimated and various emergy-based indicators are reported. Emergy money ratio of Canada and its ten provinces is estimated and is used to convert dollar values of socio-economic aspects of construction to emergy equivalents.

The results highlight the extraordinary level of renewable and natural resources available in Canada. Analysis performed for each province enhanced the accuracy of the study and also point out areas with the highest resource consumption and emergy density. Moreover, emergy maps for Canada are generated in the form of emergy geography. These maps are multi-dimensional illustrations that show resource consumption, emergy per person, and emergy density across Canada. The characterizations of different areas can be used for future land planning and management at the both federal and provincial levels. As suggested by Pulselli et al. (2008), the accuracy of emergy evaluation and geographies could be further increased by improving the methods and policies for data collection. In addition, adoption of techniques such as of Geographic Information Systems (GIS) enhances the quality of regional emergy evaluation. This approach could be adopted to develop a dynamic framework for regional studies to provide decision support for sustainable development.

5 Chapter: Em-Green Sustainability Rating System and the Decision Support Tool

In this chapter, the Em-green sustainability rating system is outlined and the corresponding decision support tool is developed.

5.1 Em-green sustainability rating system

Evaluation of a building by the Em-green rating system requires a sequential process, as described in this section. Initially, a set of questionnaires was designed to assist understanding of the life cycle of building. The questionnaire consists of four parts and provides the necessary life-cycle data of the project for analysis:

- General project information
- Construction materials and structural systems data
- Annual operational energy consumption of the building during use phase
- End-of-life scenario after demolition

A sample questionnaire is provided in Appendix A. The building is analyzed for triple bottom line of sustainability; i.e. Environmental, economic and social assessment.

5.1.1 Environmental assessment

After extracting the quantity of construction materials from the structural/architectural documents, emergy analysis is performed to transform these values to their emergy equivalents (as discussed in chapter 3). This process covers the environmental impact of materials extraction, manufacturing, transportation and construction phases.

Operational energy consumption of building during its use life is sensitive to the location of building. In other words, source of electricity production in British Columbia (mainly hydro) is different from Alberta (mainly coal) and Ontario (partially nuclear). These variations in generation processes lead to different emergy values. The emergy values for primary sources of energy in Canada are shown in Table 5.1.

Table 5.1 Emergy value of operational energy sources in various Canadian cities (per year)

	Emergy equivalent for each city (sej/year)				
Annual energy consumption	**Toronto**	**Quebec City**	**Vancouver**	**Calgary**	**Montreal**
1 kwh of Electricity	9.52E+11	2.66E+11	2.56E+11	2.54E+11	2.66E+11
1 m^3 of Natural gas	1.99E+12	1.99E+12	1.99E+12	1.99E+12	1.99E+12
1L of Diesel	2.71E+12	2.71E+12	2.71E+12	2.71E+12	2.71E+12

The evaluation of emergy used in demolition, recycle and disposal is based on a study by Brown and Buranakam (2003). Table 5.2 shows the unit emergy of various end-of-life scenarios.

Table 5.2 Emergy of end-of-life scenarios (Brown and Buranakam, 2003)

Demolition (sej/g)	Collection (sej/g)	Sorting (sej/g)	Landfilling (sej/g)
1.50e08	2.20e07	6.70e06	1.00e07

Table 5.3 shows the emergy the amount of saved emergy as a result of recycling construction materials at the end of a building life-cycle.

Table 5.3 Emergy of recycled materials

Recycled Materials	Emergy saved (sej/g)
Concrete with recycled aggregates	**1.00E+09**
Clay brick	**1.42E+08**
Recycled steel	**2.83E+09**
Recycled aluminum	**1.17E+10**
Recycled lumber	**8.79E+08**
Recycled plastic	**8.79E+08**
Recycled Ceramic tile	**1.00E+09**

5.1.2 Socio-economic assessment

The main focus of current leading building rating systems are on environmental impacts of construction. In this study, some socio-economic impacts of construction are addressed in addition to the lifecycle environmental impacts.

For economic assessment, Life-cycle cost of building, as an important factor in construction industry decision making, is considered in the Em-green sustainability evaluation. The cost of each lifecycle stage is converted to its emergy equivalent using the corresponding emergy money ratio of the construction location (as discussed in chapter 4).

As defined in the objectives of research thesis, the only criteria considered for social assessment is the lifecycle building impact on human health: respiratory effect.

Emergy loss due to building impact on human health is calculated based on a study by Reza et. al, (2012):

$$EL_{HH} = \sum m_i * DALY_i * E_p P \quad \text{(eq. 2)}$$

where,

m_i is the amount of lifecycle emission (kg)

DALY is a disability adjusted life years per unit emission (yr/kg)

E_PP is the total annual emergy per population of the construction location (sej/person/yr) as calculated in Chapter 4.

In this study, human health respiratory effects as a result of lifecycle construction activities are considered by calculating the amount of particulate matter emission.

Particulate matter (PM) are tiny subdivisions of solid matter suspended in the air and can cause serious human health problems. Particulate matter pollution is estimated to cause 22,000-52,000 deaths per year in the United States and 200,000 deaths per year in Europe (Mokdad, 2004). The effects of inhaling particulate matter that have been widely studied in humans and animals now include asthma, lung cancer, cardiovascular issues, birth defects, and premature death. The size of the particle is a main determinant of where in the respiratory tract the particle will come to rest when inhaled. Particles less than 2.5 micrometers in diameter (PM2.5) are referred to as "fine" particles and are believed to pose the largest health risks. Because of their small size (less than one-seventh the average width of a human hair), fine particles can lodge deeply into the lungs (US EPA, 2008).

Table 5.4 shows the human health respiratory effect potential in the unit of PM 2.5 equivalent for all construction materials studied for the research thesis.

The disability-adjusted life year (DALY) is a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death. DALYs are calculated by taking the sum of these two components:

$$DALY = YLL + YLD \quad \text{(eq.3)}$$

where,

YLL is the Years of life lost

YLD is Years Lived with Disability

The DALY relies on an acceptance that the most appropriate measure of the effects of chronic illness is time, both time lost due to premature death and time spent disabled by disease. One DALY, therefore, is equal to one year of healthy life lost (Havelaar, 2007). DALY of particulate matters is 3.75e-4 yr/kg (Reza et al., 2012).

Table 5.4 HH respiratory effect of construction materials

Material	unit	HH resp. effect. (kg of PM 2.5 eq)
Portland cement Concrete	kg	2.58E-03
Concrete Block	kg	7.26E-04
Mortar	kg	2.48E-03
Fly Ash Concrete	kg	2.59E-03
High Volume Fly Ash Concrete	kg	2.57E-03
Cedar wood - cladding	kg	1.90E-03
Concrete break - cladding	kg	2.24E-03
Natural stone - cladding	kg	4.29E-03
Vinyl siding	kg	3.38E-03
Gypsum board	kg	3.91E-03
Fiberglass batt insulation	kg	9.19E-03
Polystyrene insulation	kg	1.33E-03
Organic felt roofing	kg	2.87E-03
Polyethylene roofing	kg	6.13E-03
EPDM membrane roofing	kg	1.96E-03
PVC membrane roofing	kg	2.26E-03
Asphalt roofing	kg	2.51E-03
ceramic tile	kg	3.23E-03
Aluminum	kg	1.51E-02
Solvent based alkyd paint	kg	5.90E-03
Standard glazing	kg	1.44E-02
Reinforcing rebar	kg	1.68E-03
Steel nails	kg	1.65E-03
Wide flange section (I) steel	kg	2.08E-03
Hollow structural steel section	kg	2.21E-03
Galvanized steel sheets	kg	7.98E-04
Softwood lumber	kg	1.61E-03
Plywood lumber	kg	1.92E-03
Glulam wood beam	kg	1.84E-03
Bamboo	kg	7.98E-04
Linoleum	kg	1.28E-03
Concrete footing - 200mm thick	$1m^2$	1.30E-01
Concrete block wall	$1m^2$	2.68E-01
Concrete tilt-up wall - 200mm thick	$1m^2$	1.40E-01
Wood Stud wall	$1m^2$	5.90E-03

5.1.3 Em-green evaluation mechanism

Unlike major rating systems in Canada (including LEED) that are mainly designed based on conscious or expert opinions, Em-green evaluation is based on actual building performance throughout its life cycle. The certification mechanism was designed based on the climate change and global warming potentials.

The main goal of Em-green certification is to avoid global warming. Analysis of the earth's temperature proves that global warming is happening faster than ever and humans are responsible for their actions to avoid it. Global warming is caused by releasing Green House Gases (GHG) into the atmosphere. This is a major problem because global warming destabilizes the delicate balance that makes life on this planet possible. Just a few degrees in temperature can completely change the world, and threaten the lives of millions of people around the world (350.org, 2012).

Environment Canada's goal to address climate change and air quality is to reduce Canada's total greenhouse gas (GHG) emissions 17% by 2020 (Environment Canada, 2012). Figure 5.1 shows the national GHG emission of Canada from 1990-2010.

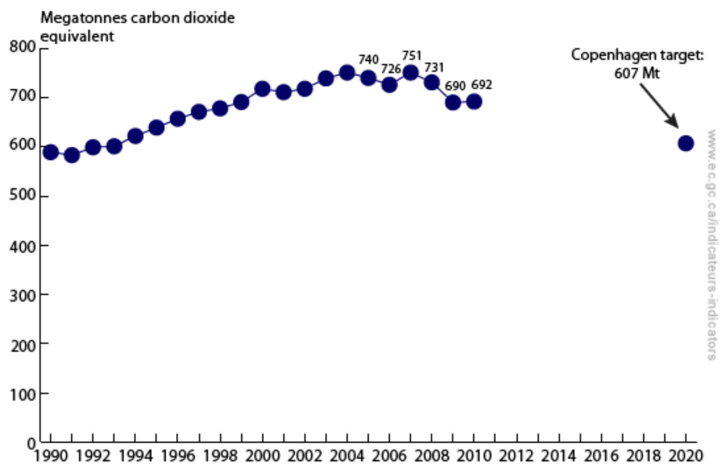


Figure 5.1 GHG emission of Canada (Environment Canada, 2012)

Em-green sustainability evaluation mechanism is based on this goal. As a first step, a base building that represents a typical construction project in Canada needs to be identified and emergy evaluation is performed for the building. To do so, large number of buildings (around 100 cases) with various structural systems, sizes and climate conditions in Canada need to evaluated for their emergy value. The base building, representing Canadian construction trend, can be selected then based on this extensive emergy evaluation.

For the base building, the emergy value per unit area of construction (sej/m^2) of the building is calculated and is assumed to be the average emergy per unit area of construction projects in Canada. This value is referred to as the Em-G value of the building. Emergy evaluation for 100 buildings across Canada to set the base line is a time consuming process that requires access, analysis and evaluation of these buildings. Therefore, development of base building is beyond the scope of the research thesis and only the evaluation mechanism is outlined.

Figure 5.2 shows the logo of the Em-green sustainability rating system.

Figure 5.2 Em-green sustainability rating system logo

Em-green sustainability rating system has three levels: green maple leaf, orange maple leaf and yellow maple leaf. Green maple leaf is the highest level of certification, where the Em-G value of the building is 17% less than the Em-G value of the base building. 17% reduction compare to the base building is the projection of Environment Canada’s goal of reducing the current GHG emission level by 17% to avoid the climate change and global warming.

Orange maple leaf corresponds to 10% reduction of Em-G value of the building compare to the base building, which means the building performance is better than the average Canadian performance but still higher than the accepted.

Yellow maple leaf corresponds to Em-G value of the base building, where building performance is at the level of current average construction performance. Yellow maple leaf shows that the building performance is not sustainable and actions need to be taken to improve performance. The action can be choosing low-emergy intensity construction materials, using greener technologies for operational energy of the building, recycle/reuse of construction materials at the end of its life cycle, reduce the overall cost of building, improve the productivity and health of the occupants, etc. Figure 5.3 shows the Em-green building rating system label.

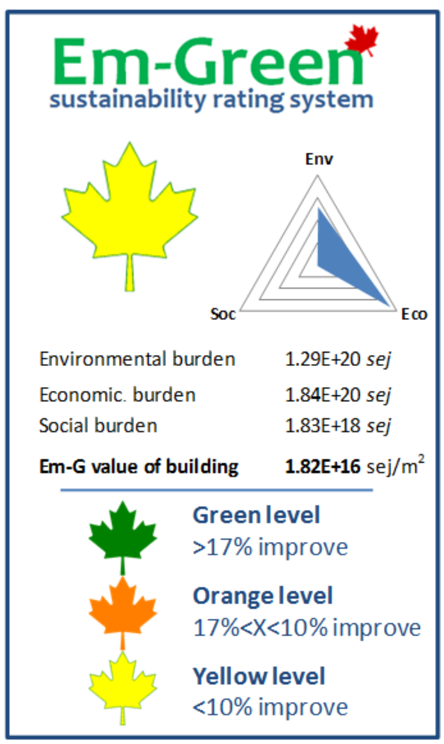


Figure 5.3. Em-Green sustainability rating system label

5.2 Em-green sustainability assessment tool for decision making

A user-friendly emergy-based decision support tool for construction projects was developed based on Em-green sustainability rating system. This decision support tool assists the design team, project manager or the project owner (as the users) to perform the sustainability evaluation of the building at early stages of the building lifecycle. .. Figure 5.4 shows the snapshot of the Em-green sustainability assessment tool cover page. There are 3 steps required for each assessment:

Figure 5.4. Em-Green cover page

1. Project Information: the user is asked to provide general information about the project, as shown in Figure 5.5. Information provided in this section such as location of project, gross area of the building and building life expectancy is used in the assessment.

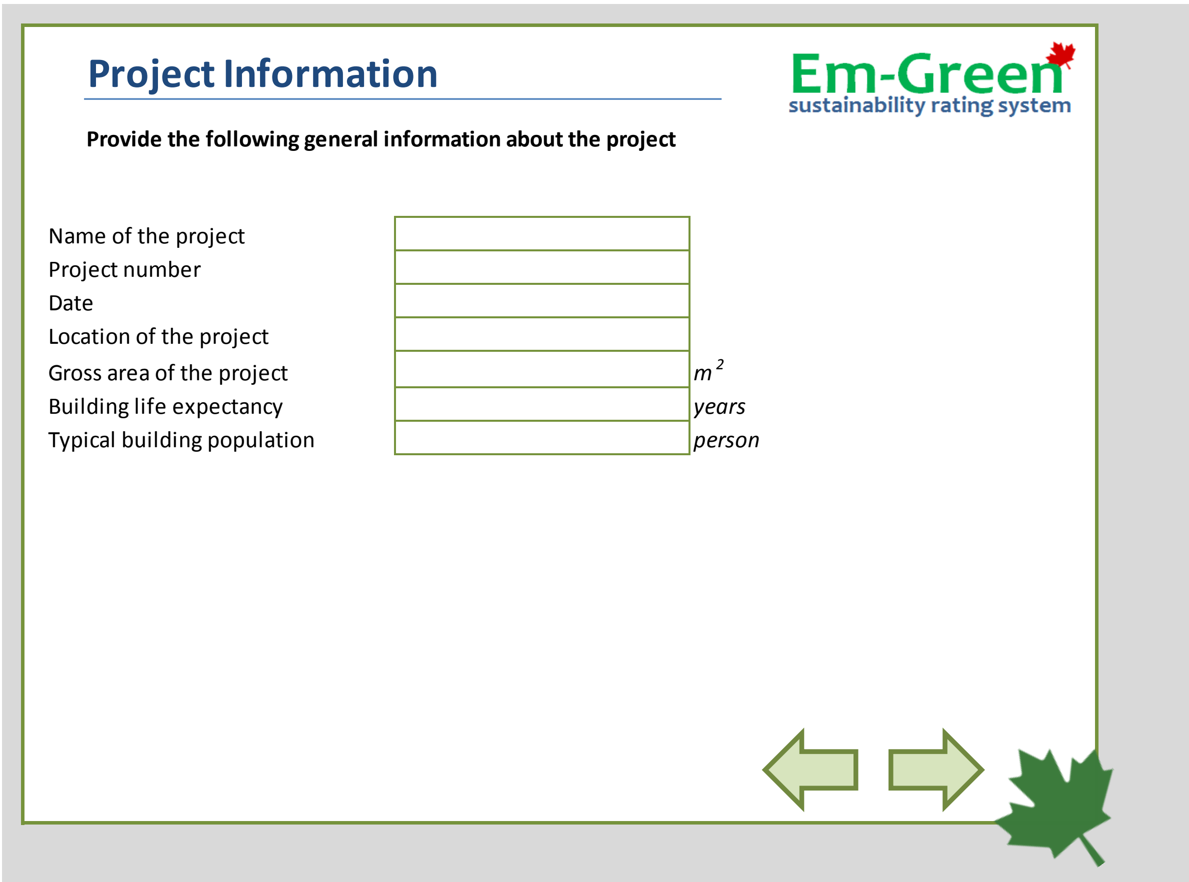


Figure 5.5. Em-Green step1 project information

2. Environmental assessment: As the core part of building evaluation, the user is required to provide project data for lifecycle environmental impact calculation by Em-Green. For part 'a', user is asked to provide quantity of construction materials out of a list of major construction materials in Canada. This step covers environmental impacts associated with material extraction, manufacturing, transportation and construction stages (Figure 5.6).

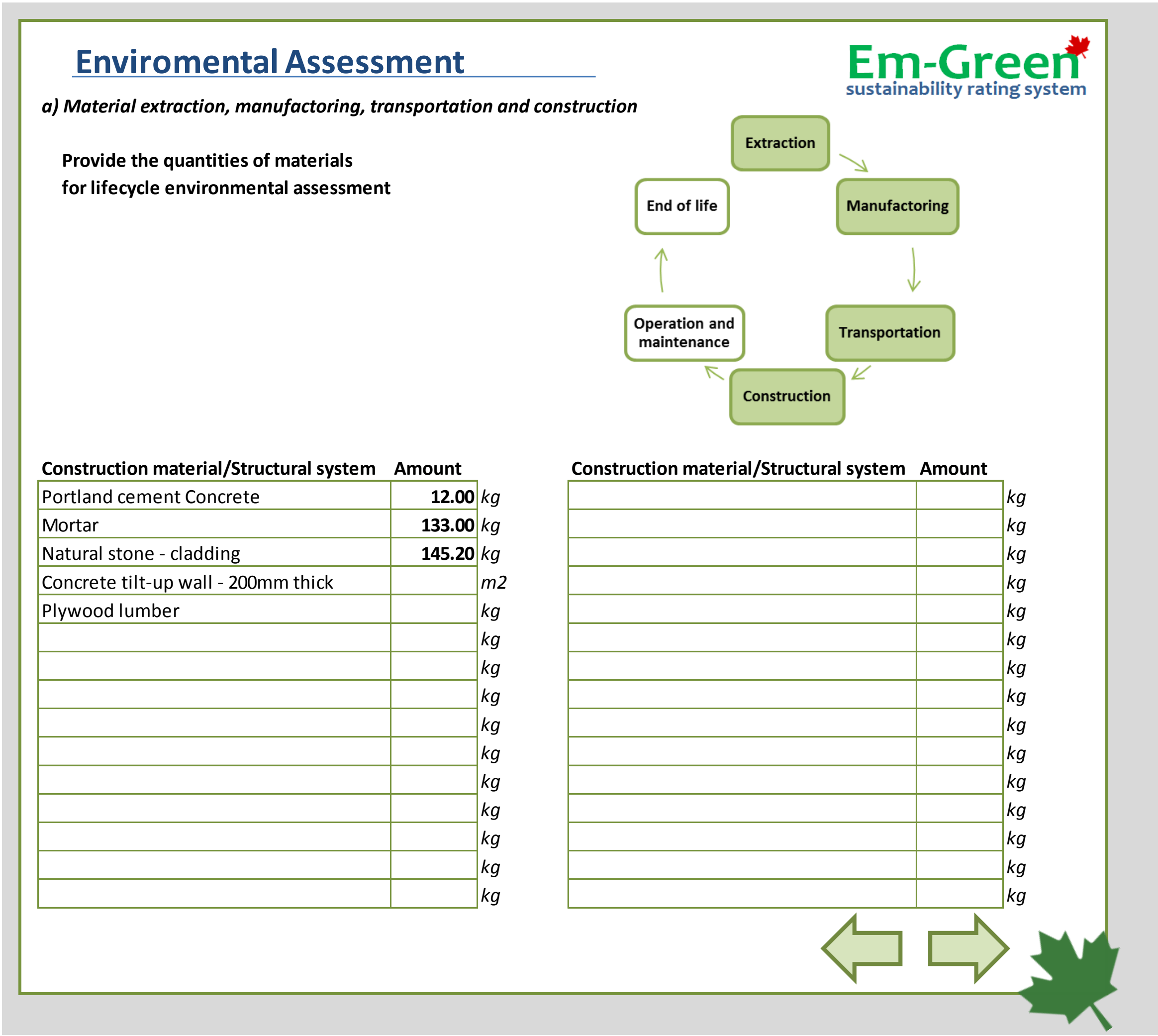


Figure 5.6. Em-Green Environmental assessment part a

For part ‘b’, user provides the type and amount of operational energy and water consumption of the building during its use phase, as shown in Figure 5.7. In part ‘c’, user provides information about end of life scenarios of the building. Demolition, recycle and landfill are the options at the end of a given building’s life cycle. This stage is shows in Figure 5.8.

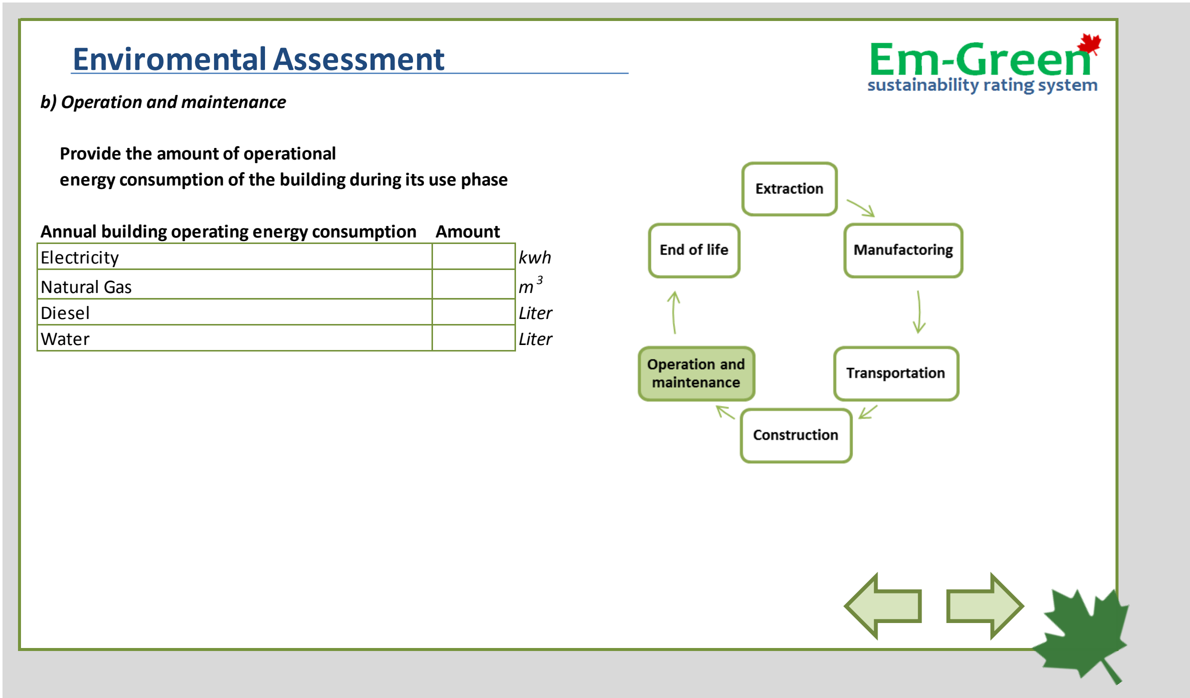


Figure 5.7. Em-Green Environmental assessment part b

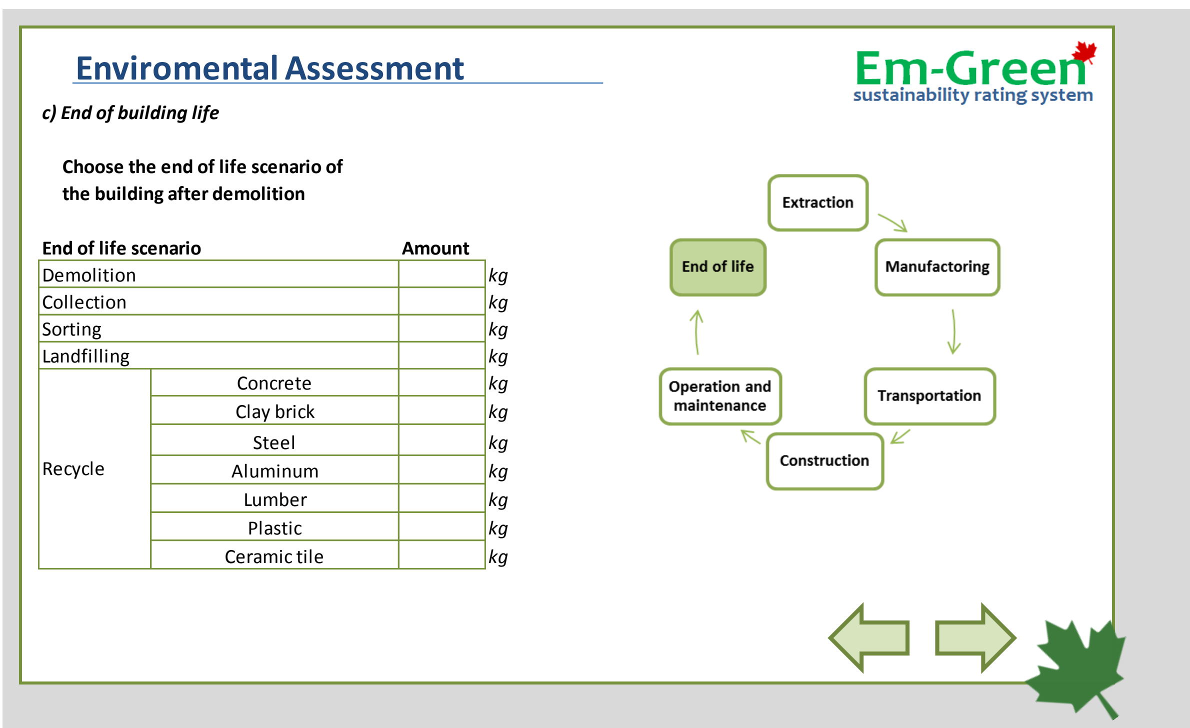


Figure 5.8. Em-Green Environmental assessment part c

3. Socio-economic assessment: Lifecycle cost of the project and emergy loss due to human health effects are the main socio-economic aspects of building assessed in the Em-green sustainability rating system (Figure 5.9).

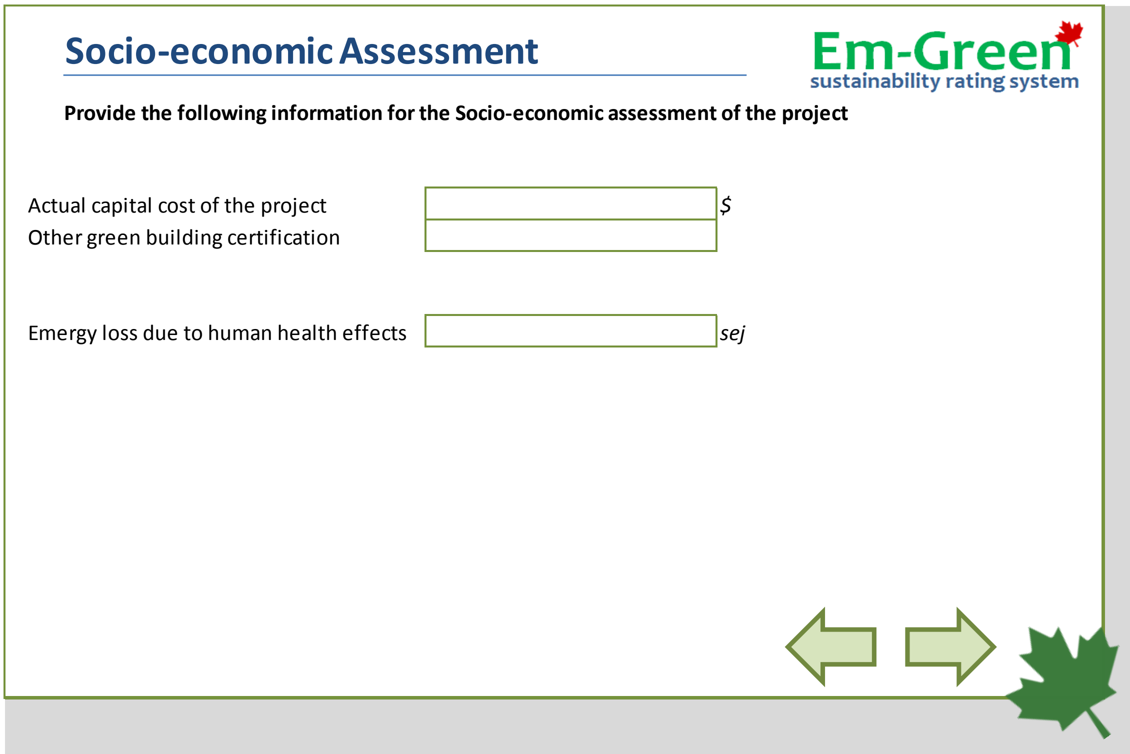


Figure 5.9. Socio-economic assessment of Em-Green

Finally the user is required to provide the Em-G value of the base building, as shown in Figure 5.10. Based on the user input in these simple steps, the building is evaluated and can be qualified for three level of certification.

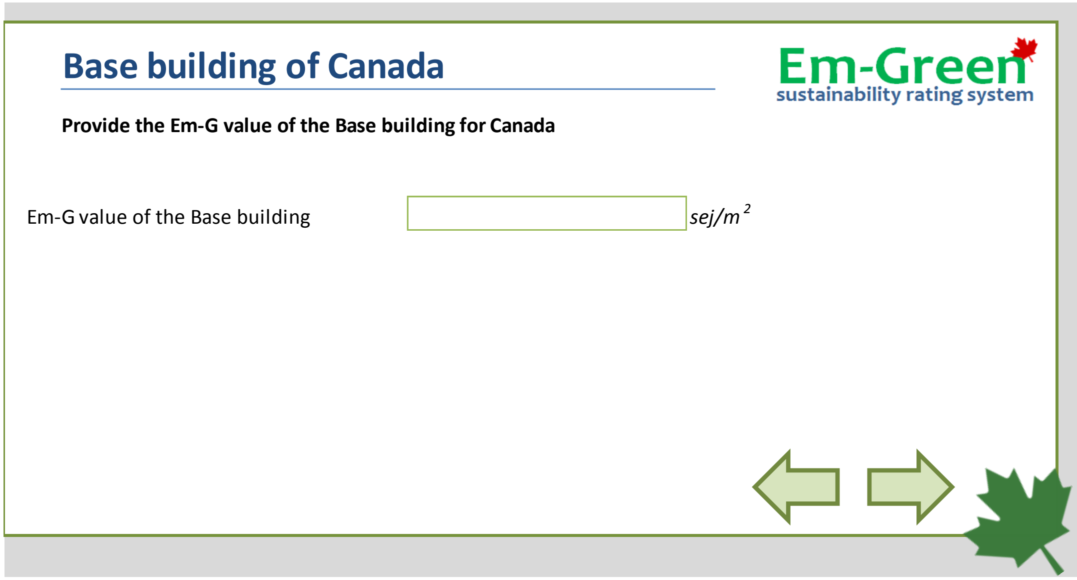


Figure 5.10 Em-G value of Base building of Canada

The certification level and the Em-Green label are presented in the result page with the project information (Figure 5.11).

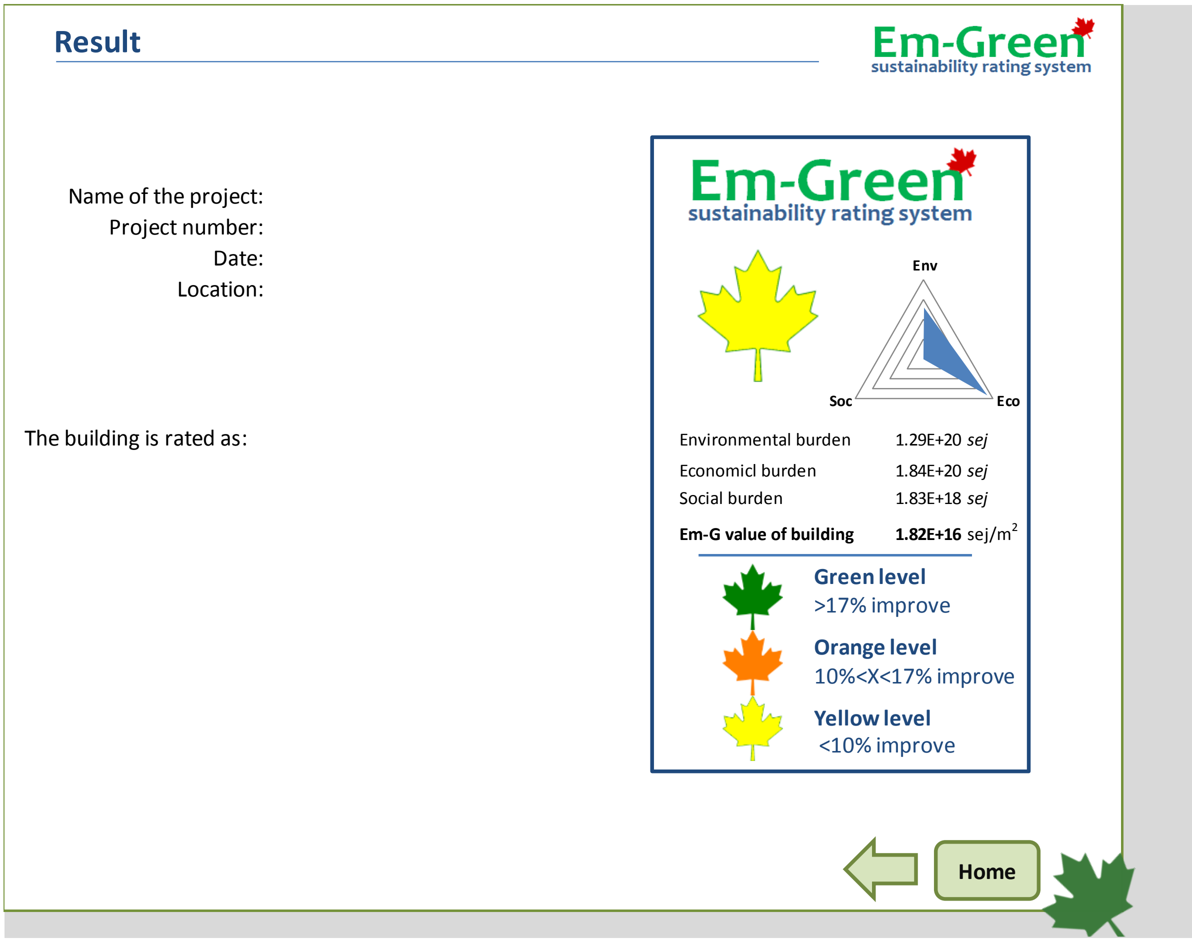


Figure 5.11.Result page of Em-Green

In Chapter 6, sustainability of two case-study buildings is evaluated using the developed Em-green sustainability rating system.

6 Chapter: Case Studies

In this Chapter, emergy evaluation is performed for two case study buildings. The first building is the Purcell residence and the second case study is the Engineering Management and Education (EME) building. Description of these two case study buildings and the emergy evaluation results are presented in the following sections.

6.1 Case study 1: Purcell residence

Purcell Residence is a student residence building located in UBC Okanagan campus in Kelowna, British Columbia. Purcell residence (Figure 6.1) is a 5-storey wood frame building with overall area of 68,000 square feet that accommodates 212 students. The building features a green roof, rooftop terrace, solar heating panels, occupancy and window sensors and heat-recovery ventilators. The building exterior finishes include brick, Swiss Pearl fiber-cement panels, aluminum louvers and aluminum/glass curtain wall. One of the main features of the Purcell residence is geothermal heating/cooling. . Geothermal heating/cooling is the direct use of inside earth temperature to generate heating for the buildings during winter and cooling during summer. Ground source heat pumps rely on an energy exchange between the air within the building being heated and the ground. Below ten feet the earth's temperature is fairly constant, generally around ~10 °C (~50 °F). During the summer when the ambient temperature of the building exceeds that of the ground heat pumps are used to pump heat from the building in to the transfer medium and is subsequently pumped through narrow pipes into the ground so that the heat can be dissipated in the earth. When the ambient temperature falls below the ground temperature the process works in reverse. Heat pumps extract heat from the ground and use it to heat the building. Following is the basic project information:

Project Size: 68,000 ft^2

Typical occupancy: 212 persons

Capital project cost: 14,977,000 $

Construction status: Completed (August 2011)

Occupancy date: September 2011

The set of structural drawings used for the analysis is included in the Appendix B1.

Figure 6.1 Purcell residence UBC Okanagan

6.1.1 Sustainability evaluation

The Purcell residence is analyzed based on the methodology outlined in Chapter 2 and sequential process described in chapter 5. Em-green sustainability evaluation tool is used perform the analysis.

6.1.1.1 Project information

Project information is retrieved from the construction documents and architectural/structural drawings and entered in the Em-green tool (Figure 6.2).

Project Information

Em-Green
sustainability rating system

Provide the following general information about the project

Name of the project	**Purcell Residnece**	
Project number	**Base Building**	
Date	**June 2, 2012**	
Location of the project	**British Columbia**	
Gross area of the project	**6,317**	*m^2*
Building life expectancy	**60**	*years*
Typical building population	**212**	*person*

Figure 6.2 Purcell residence project information

6.1.1.2 Environmental assessment

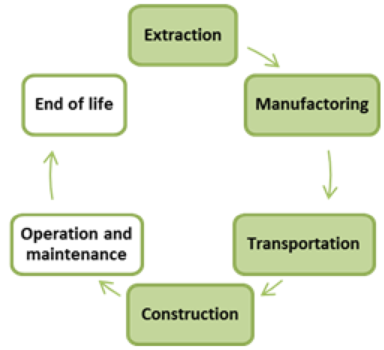
A first step, quantities of construction materials are extracted from the final design drawings for the project. This step covers the following life-cycle stages of the project: material extraction, manufacturing, transportation and construction. Figure 6.3 shows the type and quantities of the construction materials.

Enviromental Assessment

Em-Green
sustainability rating system

a) Material extraction, manufactoring, transportation and construction

Provide the quantities of materials for lifecycle environmental assessment



Construction material/Structural system	Amount	
Concrete footing - 200mm thick	293.83	m2
Fly Ash Concrete	53750.86	kg
Portland cement Concrete	11674567.62	kg
Reinforicng rebar	234566.37	kg
Sedar wood - cladding	35204.11	kg
Asphalt roofing	52342.75	kg
ceramic tile	46432.94	kg
Plywood lumber	76647.33	kg
Wood Stud wall	3090.79	m2
Solvent based alkyd paint	28.00	kg
Glulam wood beam	51098.22	kg
		kg
		kg
		kg
		kg

Construction material/Structural system	Amount	
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg

Figure 6.3 Environmental assessment – part a

Next, operation and maintenance of the building is assessed based on the actual energy performance of the building after occupation. These data were collected from the UBC properties trust office. Figure 6.4 illustrates this step.

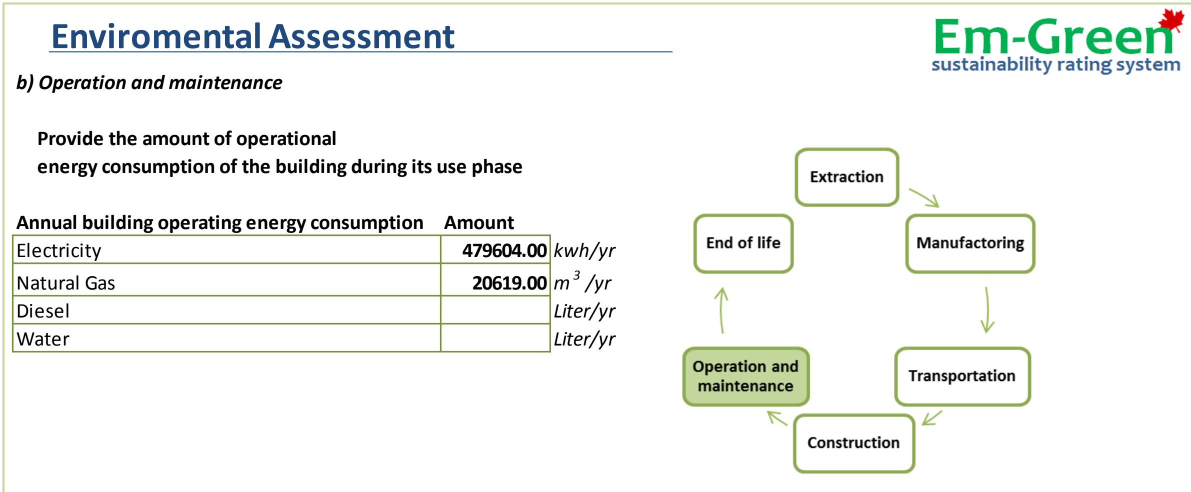


Figure 6.4 Environmental assessment – part b

At the last stage, the end of life of the structure is analyzed after demolition. The end of life scenario should reflect the current practice in Canadian construction industry. Therefore, 100% of the building is assumed to be landfilled. Figure 6.5 shows the evaluation of this stage in the Em-green tool. The value provided for amount of demolition, collection, sorting and landfilling is the sum of construction materials weights calculated in Figure 6.3.

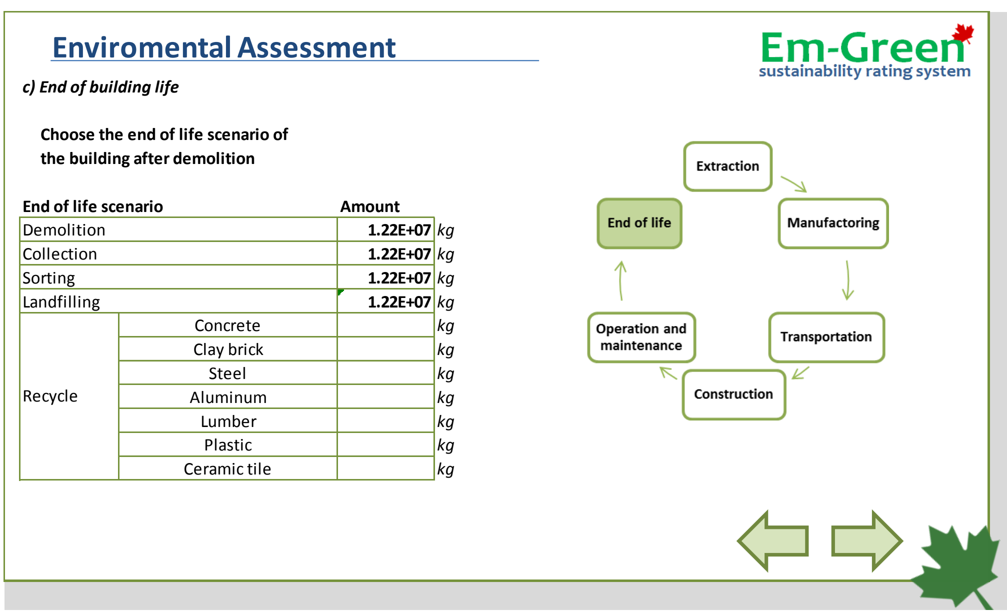


Figure 6.5 Environmental assessment – part c

6.1.1.3 Socio-economic assessment

Finally socio-economic aspect of the building is evaluated, as shown in Figure 6.6.

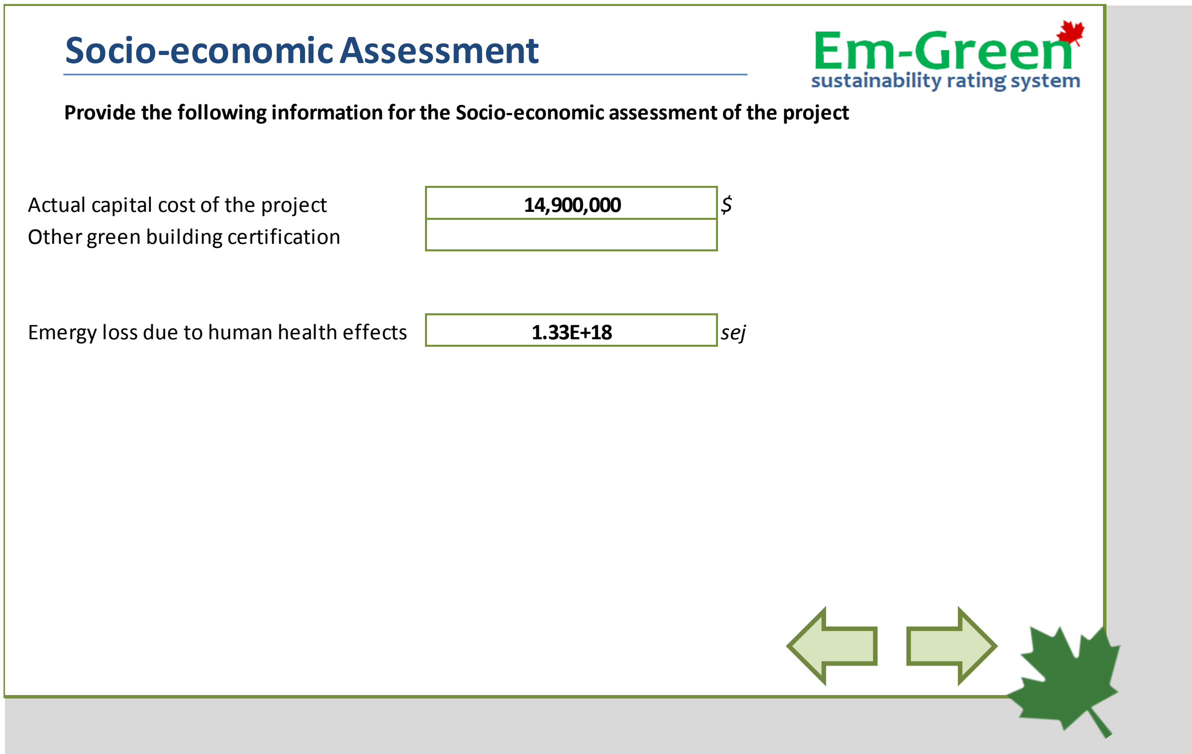


Figure 6.6 Socio economic assessment of the Purcell residence

6.1.2 Result and discussion

The Em-G value of the building is 1.24E+16 sej/m^2. Due to high Em$ value of British Columbia, the economic impact of the building is higher than the environmental impact of the structure. Figure 6.7 shows the sustainability impact distribution of the Purcell residence. Economic burden accounts for the 51%, environmental burden for 47% and the social burden 2% of the overall impact.

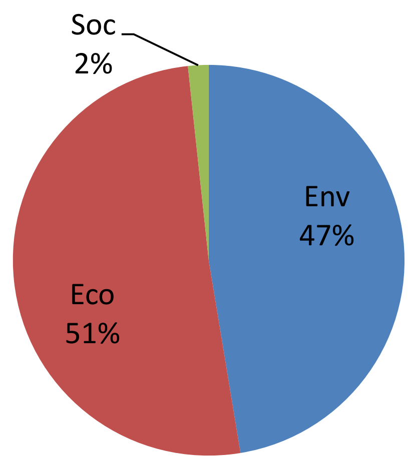


Figure 6.7 Sustainability impact distribution of the Purcell residence

Result of analysis shows that economic performance of building has the highest impact on sustainability of the built environment, yet it is not considered widely in the current building rating systems. Construction cost is a major factor in decision making in building and construction industry. This can be one of the main reasons for having a low number of construction projects to follow green building certifications (such as LEED).

The Em-G value of the first case study is compared to the second case study building in the following section.

6.2 Case Study 2: EME building

The Engineering, Management and Education (EME) building is located on the Okanagan campus of UBC in Kelowna. The EME (Figure 6.8) is a high-tech hybrid building with concrete as the main structural material. The building is organized with the three faculties arranged on either side of a central three-story glass-roofed atrium. The atrium acts as the main entrance and connects to the grand promenade through the campus. Bridges span the atrium, stairs connect the various floors, while classrooms and offices protrude into the atrium space all lit with natural daylight from above. These combine to create a stimulating environment for physical, intellectual and visual interaction. There is a radiant in-floor system in both the atrium as well as the high head lab. Four roof top heat recovery ventilators recover most of the waste heat from the exhaust. All chilled/heated water in the building is generated by high-efficiency water to water geothermal heat pumps. The classrooms are all conditioned using displacement air ventilation, and have economizers which allow outside air to provide cooling when possible. The lighting in the engineering laboratories and offices is controlled by both occupancy sensors and daylights. EME is a LEED-Gold registered building. Following is the basic project information:

Project Size: 185,991 ft^2

Typical occupancy: 400 persons

Capital project cost: 68,750,000 $

Construction status: Completed (May 2011)

Occupancy date: June 2011

Figure 6.8 EME Building UBC Okanagan

6.2.1 Sustainability evaluation

In this section, the sustainability of the EME building, as the second case study, is evaluated using Em-green sustainability rating system and assessment tool. Project information is extracted from the construction document and a set of design drawings, provided in Appendix B.2.

6.2.1.1 Project information

As the first step, project information is collected from the building documents and design drawings and entered in the Em-green tool (Figure 6.9).

Project Information

Em-Green
sustainability rating system

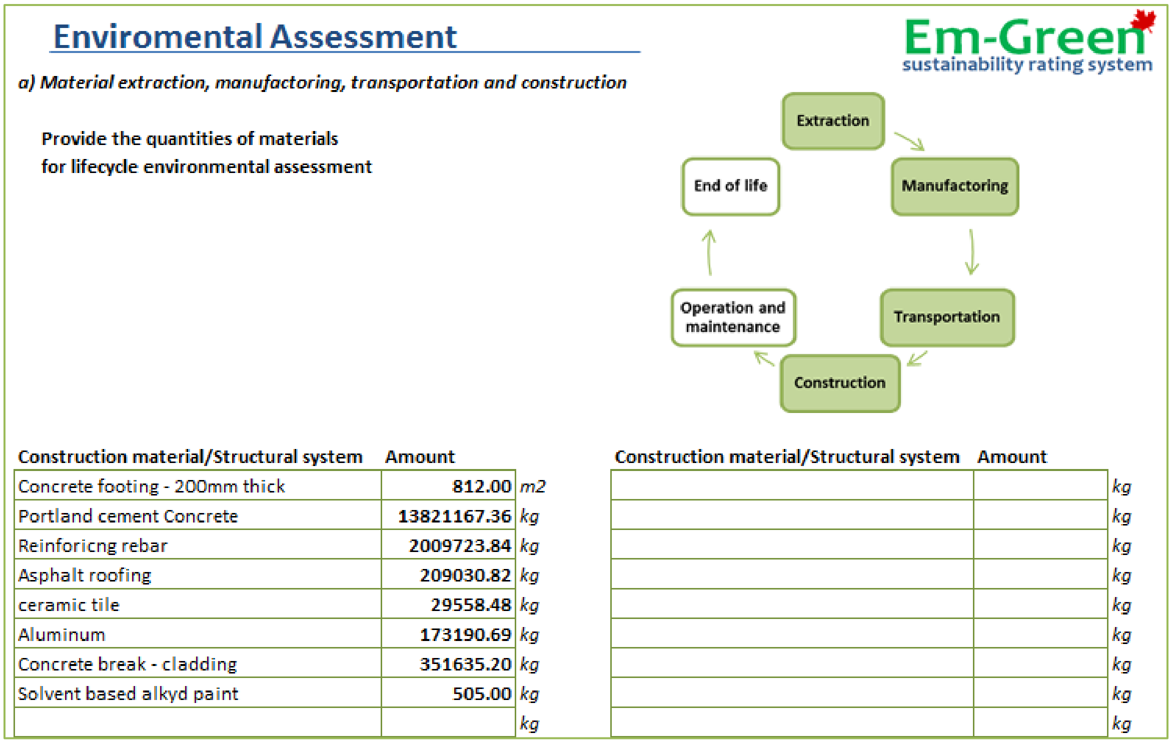
Provide the following general information about the project

Name of the project	**EME building**	
Project number	**Case study**	
Date	**June 3, 2012**	
Location of the project	**British Columbia**	
Gross area of the project	**17,273**	*m^2*
Building life expectancy	**60**	*years*
Typical building population	**400**	*person*

Figure 6.9 EME building information

6.2.1.2 Environmental assessment

As first step, quantities of construction materials are extracted from the final design drawings for the project. This step covers the following life-cycle stages of the project: material extraction, manufacturing, transportation and construction. Figure 6.10 shows the type and quantities of the materials extracted.



Enviromental Assessment

a) Material extraction, manufactoring, transportation and construction

Em-Green
sustainability rating system

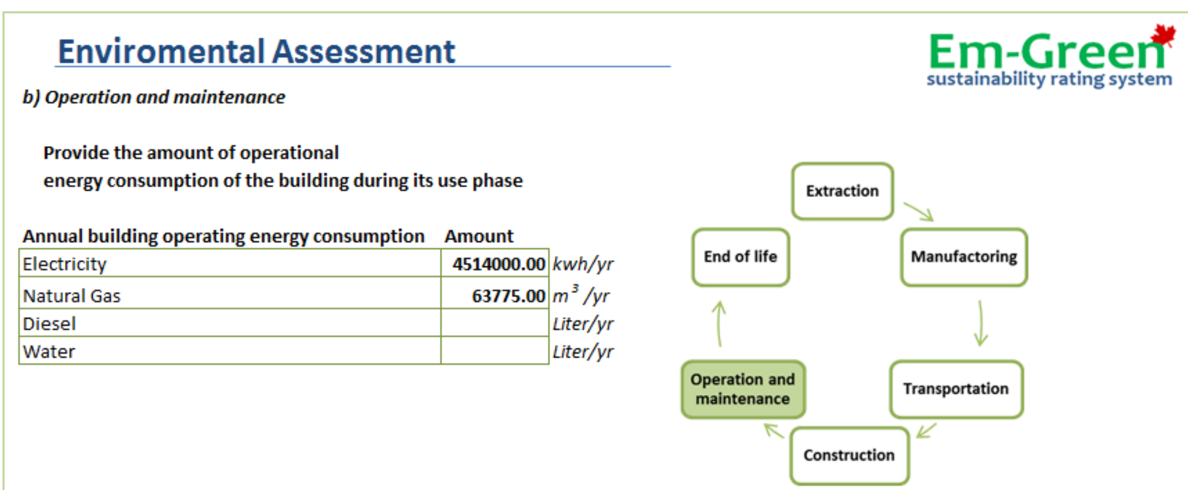
Provide the quantities of materials
for lifecycle environmental assessment

Construction material/Structural system	Amount	
Concrete footing - 200mm thick	812.00	m2
Portland cement Concrete	13821167.36	kg
Reinforicng rebar	2009723.84	kg
Asphalt roofing	209030.82	kg
ceramic tile	29558.48	kg
Aluminum	173190.69	kg
Concrete break - cladding	351635.20	kg
Solvent based alkyd paint	505.00	kg
		kg

Construction material/Structural system	Amount	
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg
		kg

Figure 6.10 Environmental assessment of EME building – part a

Next, operation and maintenance of the building is assessed based on the actual energy performance of the building after occupation. These data were collected from the UBC properties trust office. Figure 6.11 illustrates this step.



Enviromental Assessment

b) Operation and maintenance

Em-Green
sustainability rating system

Provide the amount of operational
energy consumption of the building during its use phase

Annual building operating energy consumption	Amount	
Electricity	4514000.00	kwh/yr
Natural Gas	63775.00	m^3 /yr
Diesel		Liter/yr
Water		Liter/yr

Figure 6.11 Environmental assessment of EME building – part b

Since there is no actual plan for the end of life of the EME building, scenario analysis was performed for this section considering three scenarios:

- Scenario 1: 100% of the building materials is landfilled after demolition.
- Scenario 2: 50% of the building materials is landfilled and 50% of concrete, steel and aluminum are recycled.
- Scenario 3: 100% of the major construction materials (steel, concrete and aluminum) is recycled.

Figure 6.12 shows the Scenario 1 for end of life of EME building, where whole weight of construction materials is sent for landfill, after demolition and collection.

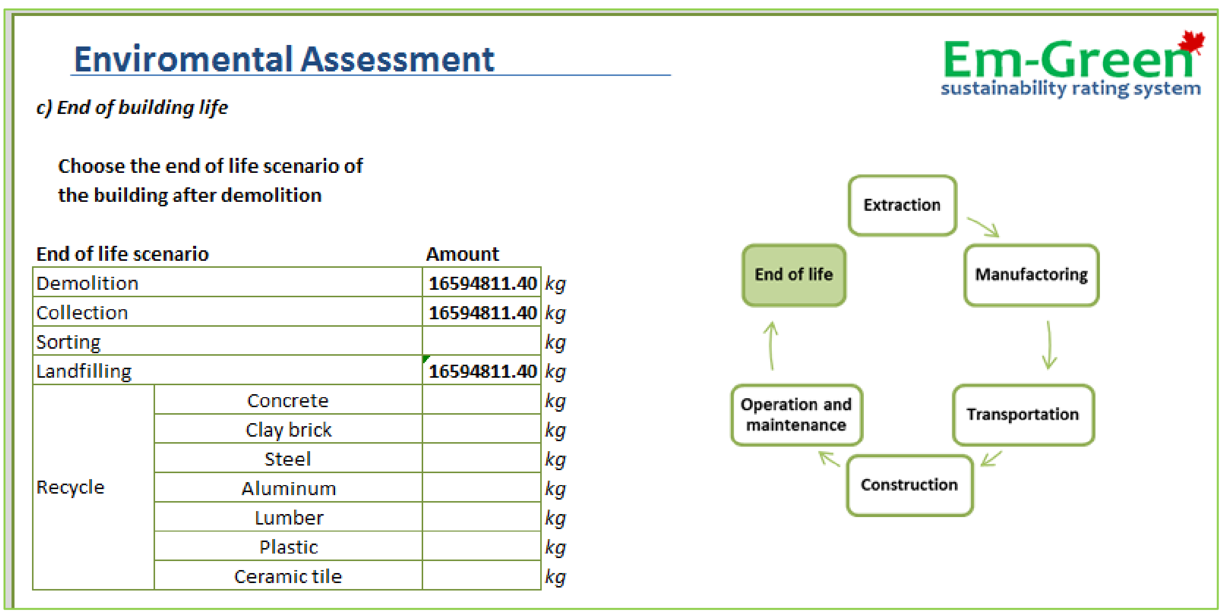


Figure 6.12 Environmental assessment of EME building – part c

6.2.1.3 Socio-economic assessment

Finally socio-economic performance of the building is assessed based on the capital cost of the project and emergy loss due to human health effects. The project is LEED Gold building that is considered in the evaluation (Figure 6.13)

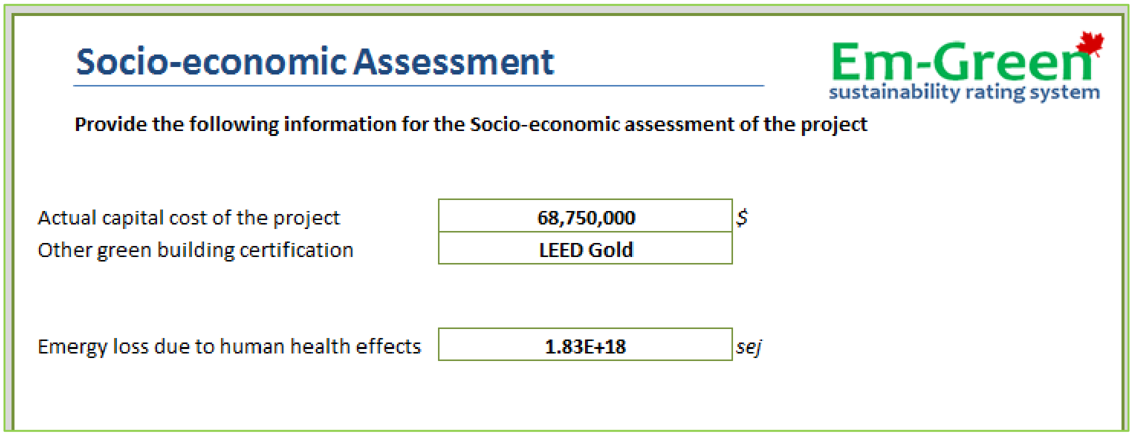


Figure 6.13 Socio-economic assessment of EME building

6.2.2 Result and discussion

The Em-G value of the building is 1.82E+16 sej/m^2. Emergy due to economic burden (1.84E+20 sej) has the highest impact followed by environmental burden (1.29e20 sej) and social burden (1.83E+18 sej). Figure 6.14 shows the sustainability impact distribution of the EME building. Economic burden accounts for the 58%, environmental burden for 41% and the social burden 1% of the overall impact.

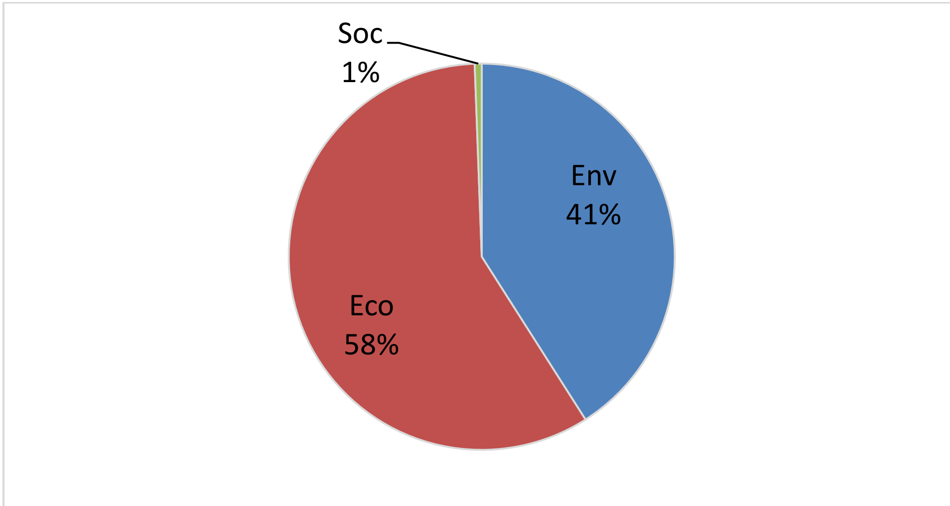


Figure 6.14 Sustainability impact distribution of the EME building

Figure 6.15 illustrates the impact contribution of each lifecycle stage for the EME building. As can be seen, operation and maintenance stages account for 60% of the weight and have the highest impact on sustainability. Material extraction, manufacturing, transportation and construction stages account for 38% of the weight. Demolition of the structure and 100% landfilling has 2% of the weight.

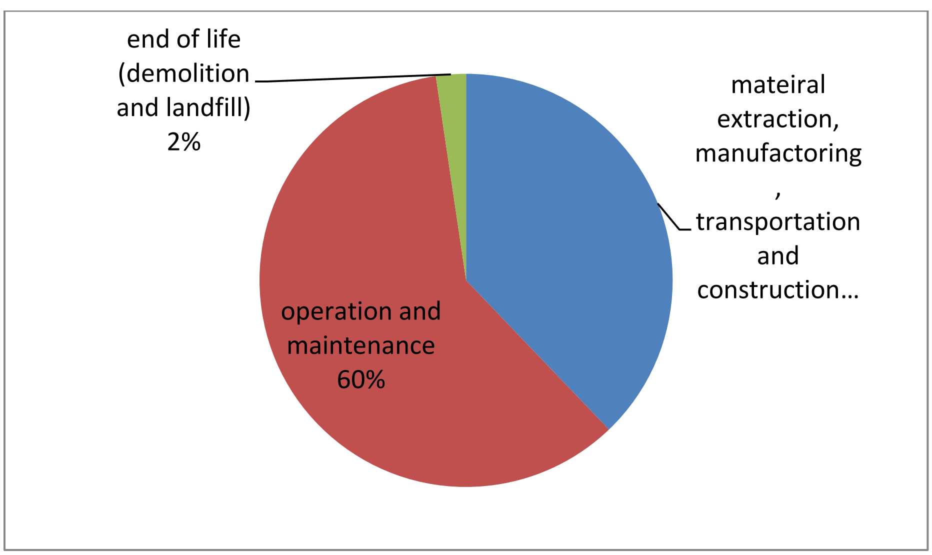


Figure 6.15 sustainability assessment of lifecycle stages

The result of the assessment shows that post construction stages have the major environmental impact and need to be considered carefully. These stages are usually ignored in the assessment mechanism of current building rating systems.

Figure 6.16 shows the emergy comparison of the EME building and the Purcell residence per unit of area (sej/m^2). The results show that the per-unit environmental and social performance of the two buildings are similar. However, the unit cost of the EME building is much higher than the Purcell residence, making the Em-G value of the building high therefore resulting in poor overall sustainability performance.

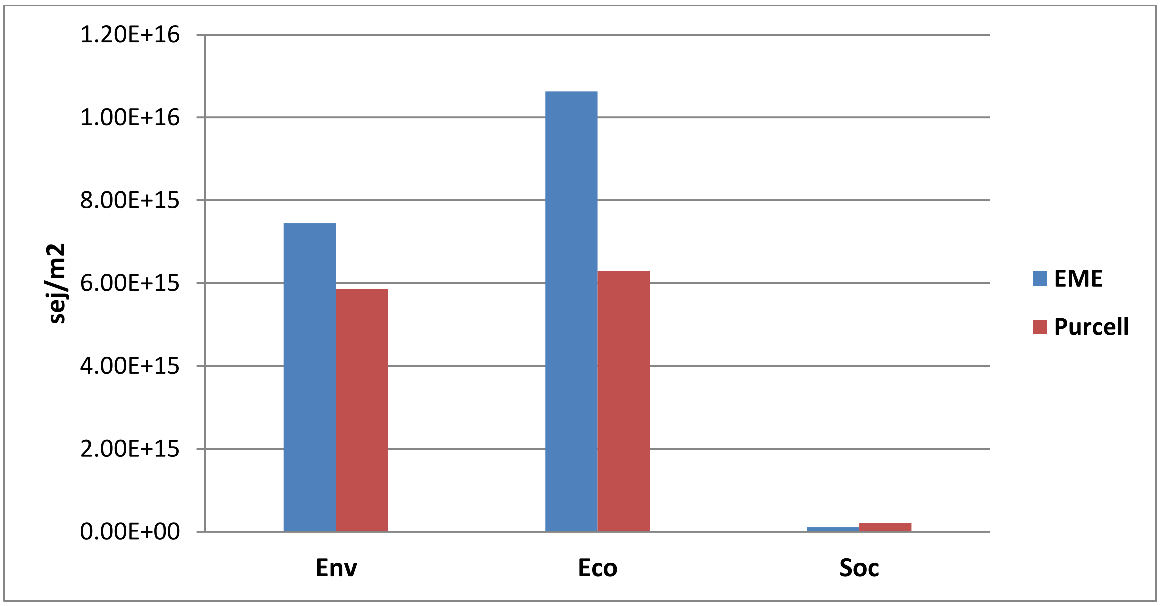


Figure 6.16 Comparison of EME and Purcell

6.2.2.1 Scenario analysis: end of life options

Three end-of-life scenarios were considered for the EME building and the corresponding sustainability performance is evaluated using Em-green tool. For the 1st scenario 100% of the building materials are landfilled after demolition. In Scenario 2, 50% of the building materials are landfilled and 50% of the structural elements such as concrete and steel are recycled. And for the last scenario 100% of the major construction materials are recycled. Table 6.1 shows the Em-G values of these scenarios.

Table 6.1 End of life scenarios

Scenario	Em-G value (sej/m^2)
Scenario 1	1.82E+16
Scenario 2	1.77E+16
Scenario 3	1.71E+16

Recycling 50% of construction materials improves the Em-G value by 3% and recycling 100% of structural materials improves the Em-G value by 7%.

6.2.2.2 Scenario analysis: location of construction

As previously mentioned, the location of construction plays an important role in assessing the sustainability of buildings. In this section, the sustainability of EME building is evaluated assuming the building is located in four different provinces: British Columbia, Alberta, Ontario and Quebec. Figure 6.17 shows the result of the analysis. As can be seen, the overall Em-G value of the building varies in each province. This is mainly due to different Em$ value, various transportation distances, and differences in the source of operational energies of each province. Also, distribution of each burden (i.e. environmental, economic and social) changes in each province. For example, in Ontario, environmental impact is a dominant factor, while in Alberta economic impact is the major contributor. The evaluation result assists the sustainable decision making based on regional priorities.

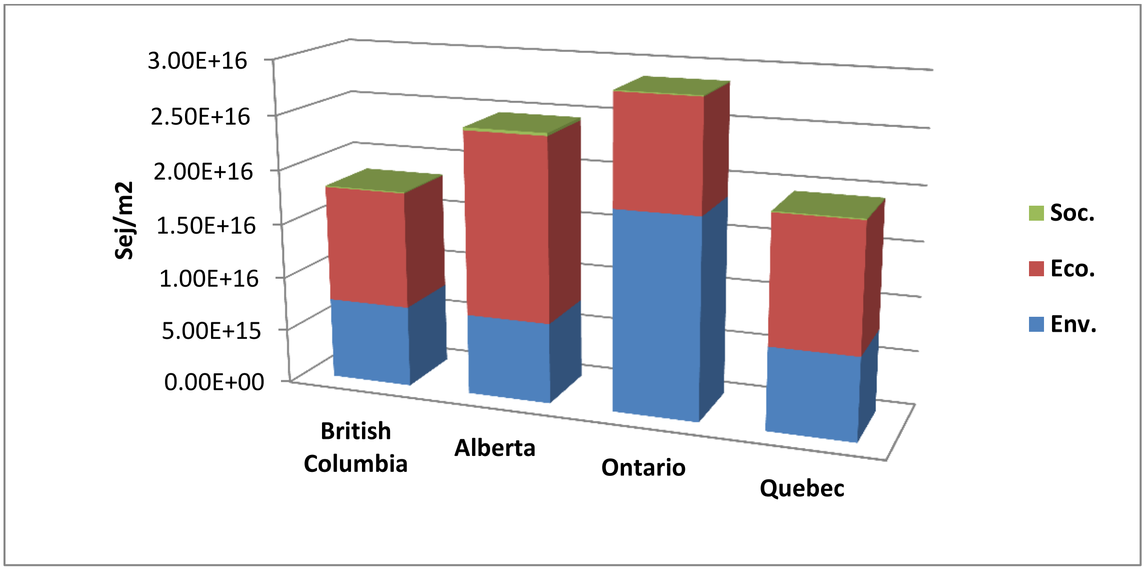


Figure 6.17 Scenario analysis: Location of construction

7 Chapter: Conclusion and Recommendations

In this chapter the conclusion of the research thesis is presented, strengths and limitations of this study are outlined and recommendations are provided for future research directions.

7.1 Conclusion

Due to the weaknesses in current sustainability rating systems, the construction industry needs a more comprehensive method that covers the lifecycle of building materials and provides a better estimation of building's environmental impact.

This research targets to address weaknesses in the current green building rating systems in North America, by implementing emergy accounting to assess environmental and associated socioeconomic impacts of the construction projects over their lifetime.

The main objective of this research is to develop an emergy-based sustainability rating system for Canadian construction projects, named the "Em-Green sustainability rating system". This sustainability evaluation system has the following characteristics:

- It is a user-friendly framework for building and construction industry in Canada
- It is based on the emergy methodology
- It includes Triple Bottom Line (TBL) of sustainability- i.e.: environmental, social, and economical.
- It covers the complete life-cycle of buildings (Cradle-to-Cradle), including resource extraction, manufacturing, transportation, construction, operation, and maintenance and demolition (landfill or recycle).

Methodology of developing the Em-green rating system is outlined in Chapter 2. Following are the deliverables of this research study:

- An emergy database for major Canadian construction materials and structural systems (Chapter 3)
- An emergy accounting of Canada and its provinces by calculating emergy indicators, indices and emergy maps for the region (Chapter 4)
- An emergy-based building rating system that covers the triple bottom lines of sustainability: the Em-Green sustainability rating system (Chapter 5.1)
- A user-friendly building assessment tool based on the emergy database and the developed rating system (decision support tool). (Chapter 5.2)

7.2 Strengths and limitations of the thesis research

The main goal of the Em-green rating system is to evaluate sustainability of Canadian buildings and help the building industry in the necessary shift toward the green practices. Following are the main strengths and contributions of this research thesis:

- Em-green sustainability rating system considers the overall lifecycle of building (cradle-to-cradle) in the assessment.
- Beside environmental assessment as the main core of Em-green, some socio-economic impacts of construction projects (Lifecycle cost and impact of building on occupants health) are considered in the sustainability evaluation.
- Unlike major building rating systems that are judgmental and based on expert opinion, the Em-green is designed based on scientific facts to prevent global warming and climate change according to Environment Canada’s plan for 2020. The certification levels are designed based on the target of reducing GHG emission level in the atmosphere by 17% till 2020.

- The Em-green is a user-friendly sustainability assessment tool that does not require sophisticated analysis from the user-side. The data required for the analysis can be extracted from the construction documents, energy simulation model and architectural/structural drawings.
- The Em-green framework is locally designed for Canadian construction project by covering the major construction materials used in the Canadian building industry, considering the climate, geographical and population distribution of Canada.
- The emergy assessment of Canada and its provinces is a fundamental study filling the gap of missing up-to-date emergy data for Canada. The result of emergy assessment of Canada can be used in wide range of future research studies.
- The emergy database of construction materials developed in this study can be used in the future emergy studies related to building, construction and sustainability of the built environment.
- Emergy methodology used in the research study overcomes the difficulty of weighting inputs with different characteristics in multi-criteria decision making (e.g. energy inputs in Joule, resources use in gram, monetary values in $). In emergy assessment all inputs are transformed into their emergy equivalents (sej) to avoid biased judgments.
- The sustainability rating system developed in the research study is validated by assessing the sustainability of two case study buildings: one conventional and one LEED-certified building.

- The framework of the Em-green can be adopted for sustainability assessment of building industry in other nations. Also, the sustainability evaluation framework can be expanded to develop a sustainability measure for larger scale assessments, such as neighborhood development and urban planning.

The research thesis has following limitations, mainly due to lack of data, time constrains and resource limitations:

- Although Em-green includes the triple bottom line of sustainability, the main focus is on environmental impact of a building over its lifecycle. More socio-economic indicators could be considered to balance the assessment result. The main issue with the social impact of construction is that they are qualitative. For example, aesthetic views of a building and cultural values of a building are hard to quantify.
- Due to the mentioned constrains, the base building for Canada is not defined in this study. Development of the base line for Em-green sustainability evaluation system requires emergy analysis for 100 buildings across Canada. To accurately calculate the base building, a set of construction projects of different size, in various climate zones and with different structural systems need to be analyzed. The base building then can be calculated based on the normalized lifecycle performance of these construction projects.
- Deterministic approach is used in all the analysis and calculations of the research thesis. However, due to uncertainty involved in the life stages of buildings, probabilistic analysis can be performed to identify a range of possible outcomes.

- Emergy database of construction materials is limited to the major construction materials in Canada. Wider range of construction materials can be analyzed and included in the emergy-database.
- Quality of emergy maps can be enhanced using Geographic Information System (GIS) software.
- Due to the mentioned constrains, the evaluation of the Em-green sustainability rating system is limited to two case-studies from the British Columbia. More projects across Canada can be analyzed to enhance the precision of the evaluation system.
- The Em-green sustainability rating system is only compared to the current major building rating systems in North America. The comparison can be expanded by considering more building rating systems from other parts of the world.

7.3 Recommendations and future research directions

Development of the Em-green sustainability rating system in the research thesis is the first step of using emergy methodology for the overall sustainability evaluation of buildings, as the smallest unit of the built environment. The framework developed in this research thesis provides a micro-level sustainability evaluation.

Number of buildings create a neighborhood and number of neighborhoods create a community to form cities. The future step of Em-green sustainability rating system needs to focus on macro-level sustainability evaluation of the built environment by considering the neighborhood development and urban planning. The following are the recommendation to enhance this research thesis and possible future research directions:

- Perform probabilistic analysis using Monte Carlo simulation for sensitive outputs. Monte Carlo is a computerized mathematical technique that allows user to account for risk in quantitative analysis and decision making. Monte Carlo simulation provides the decision-maker with a range of possible outcomes and the probabilities they will occur for any choice of action (Palisade, 2011).

- This research study can be expanded by considering and evaluation of more socio-economic indicators to measure the performance of buildings over their lifecycle. The current focus is on the lifecycle environmental impact of the building, while human interaction with buildings (as a social aspect of sustainability) is significant.
- GIS has wide range of application in the future of this research thesis. The result of this study shows that the location of construction is a dominant factor controlling the life cycle assessment of the building. In other word, a building might be considered green in point 'A' based on the construction materials used, transportation distances, type and amount of operational energy. However the same building in point 'B' might not be considered sustainable since the source of energy generation, transportation distances and cost of construction is different. A future step of this study can be developing a layered GIS map of a geographical region (such as Canada) where each layer consists of data related to that specific location. Datasets might include: energy sources, construction materials, construction cost, population, cultural values of the region, climate condition and the seismic information.

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Appendices

Appendix A - Life cycle assessment of buildings in Canada to develop an emergy-based sustainability rating system for construction projects

PART 1. BACKGROUND

The objective of this study is to perform a comprehensive emergy-based Life Cycle Assessment (LCA) of registered green buildings in Canada. Following information for different life stages of the green building is requested.

PART 2. General project information

a) **Demographic Information (Kept confidential):**
   - Name of institution/company:______________________________________
   - Current position with the institution/company:___________________________
   - Management experience (years):____________________________________
   - E-mail address:____

b) **Project Information:**
   - Name of the Project/Building: ______________________________________
   - Location of Project: ____
   - Designer(s): ____
   - Owner(s): ____
   - Developer(s): ____
   - Year of construction and duration: ____________________________
   - Climate Zone or Heating Degree-Day Range: ______________________
   - Gross floor area (m^2): ____
   - Number of stories (above grade): ___________________________________
   - Building life expectancy (yr): _____________________________________

– Building type (i.e. commercial, institutional, industrial, multiunit residential, office): ____

– Typical building population: _________________________________

– Number of operating hours per year: _____________________________

– Name of green building certification (e.g. LEED): ____________________

– Level of certification (e.g. certified, silver, gold, platinum): _____________

– Has project received the certification? YES ☐ NO ☐

– Actual capital cost of the project including design, construction and management fees ($): ______________________________________

PART 3. Construction materials and structural systems

a) Columns and beams design information for <u>each floor</u> (or state if it is typical for all floors):

– Number of columns: ____________________________________

– Number of beams: ____

– Bay size (m): ____

– Supported span (m): _______________________________________

– Clear floor to floor height (m): _______________________________

– Design live load (i.e. 2.4 kPa, 3.6 kPa, 4.8 kPa): _____________________

– Type of Material (e.g. concrete, wood, steel): ______________________

– Compressive strength of material (e.g. concrete 20 MPa): _____________

– Reinforcing rebar type (e.g. #10M, #15M, #20M) : __________________

b) Slab design information for <u>each floor</u> (or state if it is typical for all floors):

– Floor width (m): ____

– Floor span (m): ____

– Design live load (i.e. 2.4 kPa, 3.6 kPa, 4.8 kPa): _____________________

– Type of Slab:

- ☐ Concrete Hollow Core
- ☐ Concrete Suspended Slab
- ☐ Concrete Parking garage
- ☐ Concrete precast double T
- ☐ Light frame wood truss
- ☐ Open web steel joist
- ☐ Steel joist
- ☐ Wood I joist
- ☐ Wood joist
- ☐ Wood chord and steel web truss

– Bay size (m): ____

– Type of Material (e.g. concrete, wood, steel): _________________________

– If concrete, what is fly ash content? (e.g. 25%, 35%): ___________________

– Compressive strength of material (e.g. concrete 20 MPa): ______________

– Reinforcing rebar type (e.g. #10M, #15M, #20M): _____________________

c) Foundation design information:

– Concrete footing foundation area (m^2) (L*W): _______________________

– Concrete footing foundation thickness (m): ___________________________

– Concrete footing foundation rebar size (#10M, #15M, #20M): ____________

– Concrete fly ash (e.g. 25%, 35%): ___________________________________

– Compressive strength of material (e.g. concrete 20 MPa): _______________

d) Wall design information for basement exterior walls, stair exterior walls, exterior infill walls, stair walls, and interior walls:

– Wall type:

- ☐ Concrete block
- ☐ Cast in place
- ☐ Concrete tilt up

- ☐ Curtain
- ☐ Insulated concrete form
- ☐ Steel stud
- ☐ Wood stud
- ☐ Structural insulated panel

– Wall dimensions (length and height) (m): ______________________________

– Number of opening (windows and doors): _______________________________

– Total opening area (m^2): ____

– Windows and doors material (frame and glazing type): ___________________

e) Extra building materials information:

– Concrete:

- Amount (m3): ____
- Compressive strength (MPa): ______________________________
- Fly ash content (%): ______________________________________

– Cladding (e.g. concrete brick, Fiber Cement) (m^2):

____

____

– Gypsum Board (m^2):

____

____

– Insulation (e.g. Fiberglass, Rockwool, Cellulose, expanded polystyrene, etc.) (m^2):

____

____

- Roofing (e.g. Clay tile, Mod. Bit. Membrane, PVC membrane, Ballast, etc.) (m^2 or kg):

  ____

  ____

  ____

  Other material (PVC, Glazing, Aluminum, etc.) (m^2 or kg):

  ____

  ____

PART 4. Annual operational energy consumption of the building during use phase

a) Operating energy consumption per year of the building:
   - Total electricity use (kWh/yr): ______________________________
   - Natural Gas use (m3): ______________________________
   - Liquefied petroleum gas (LPG) (liter): ______________________________
   - Heavy fuel (liter):______________ ______________________________
   - Diesel (liter): ______________________________
   - Any other type of energy use: ______________________________

     ____

b) Operating water consumption per year of the building:
   - Washing (e.g. bathroom, kitchen, etc.) (L/yr) : ______________________________
   - Irrigation water (L/yr) : ______________________________

PART 5. End-of-life scenario after demolition

- Percentage of building that is planned to go to landfill? (%): ____________
- Type and percentage (or amount) of recycled materials: (e.g. concrete, steel, aluminum, etc.): ______________________________

  ____

  ____

Appendix B Structural drawings

B.1 Purcell residence structural drawings

Figure B.1 Purcell residence

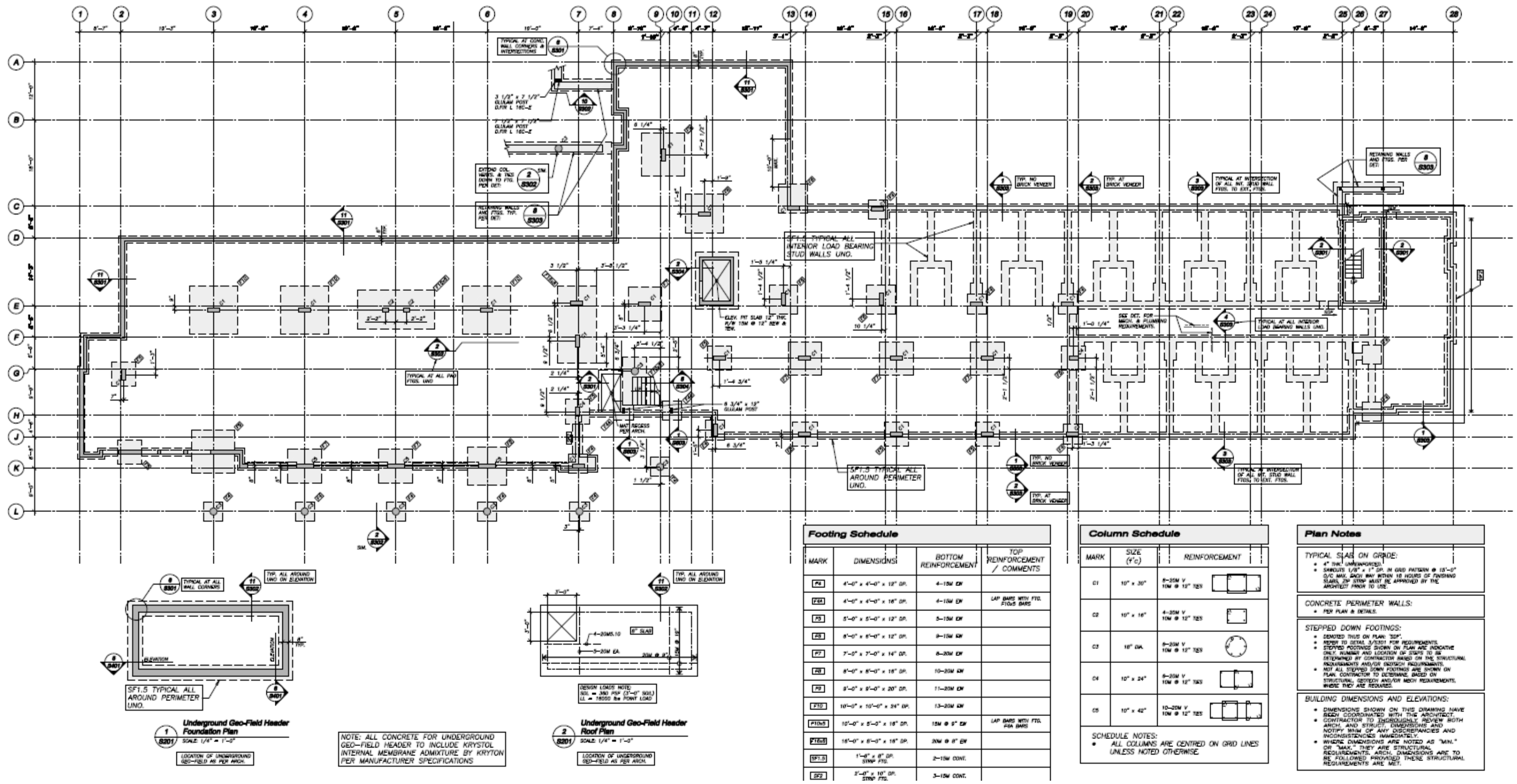

Figure B.2 Plan view of the foundation level

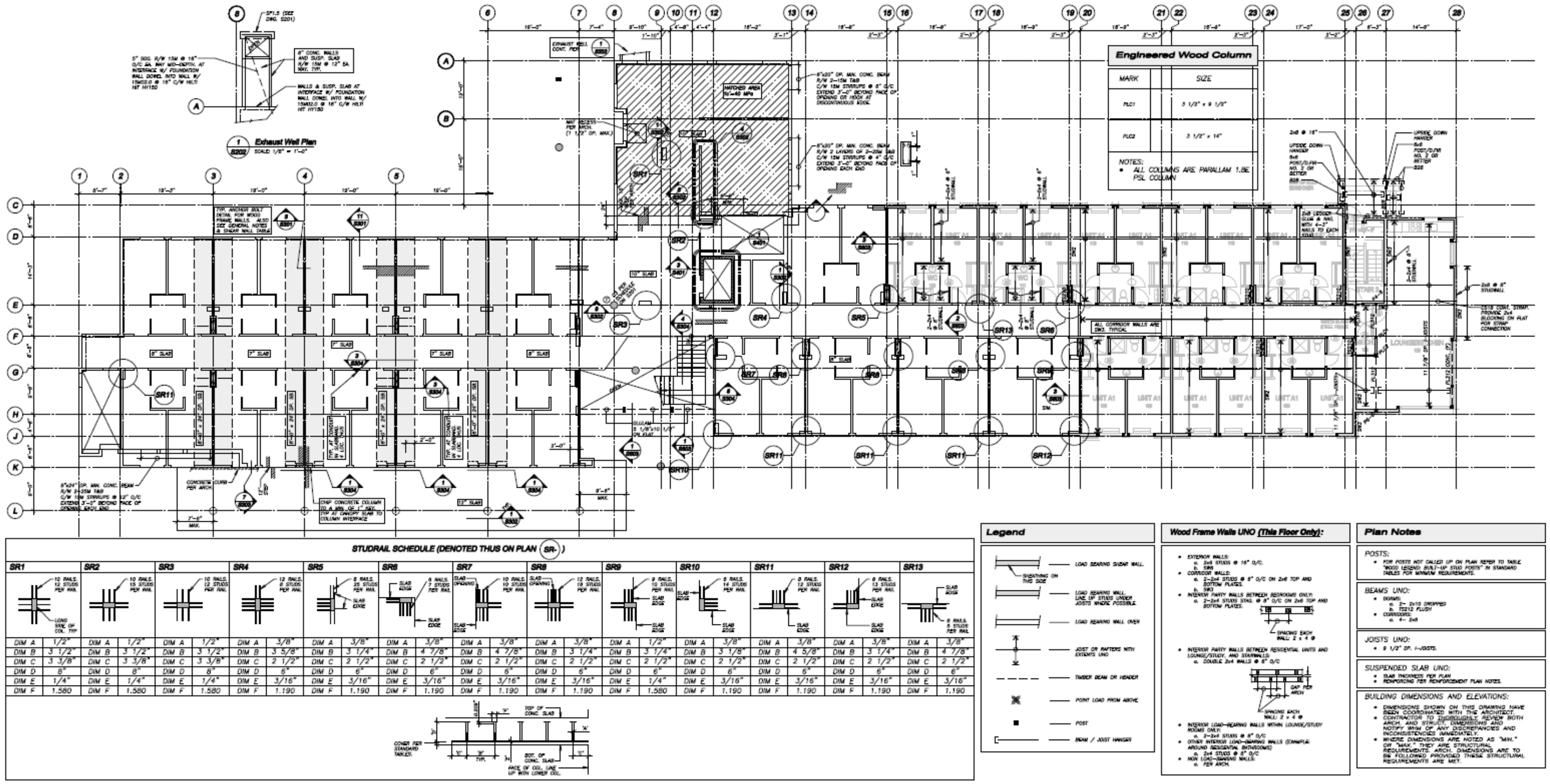

Figure B.3 Plan view of level 1

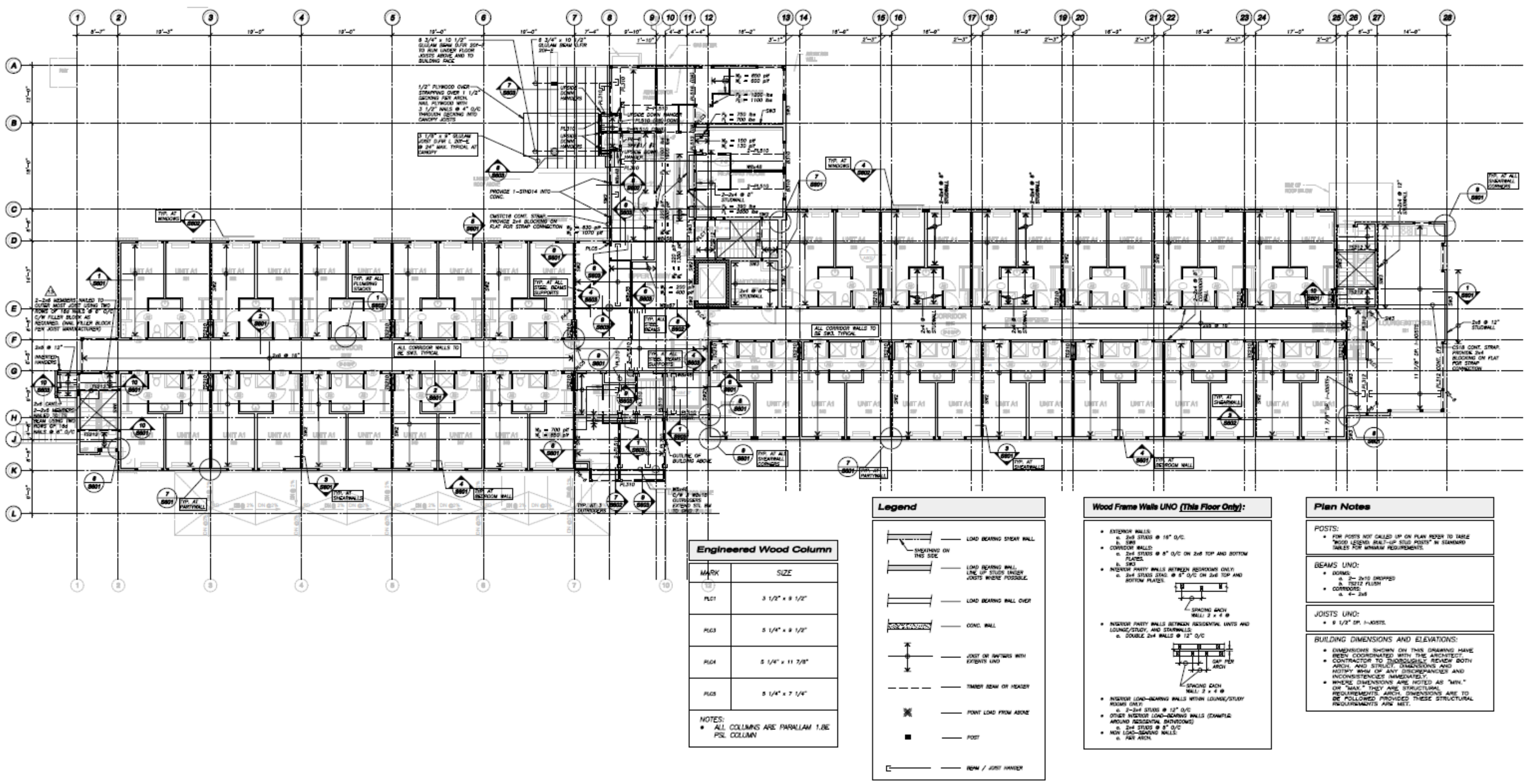

Figure B.4 Plan view of level 2

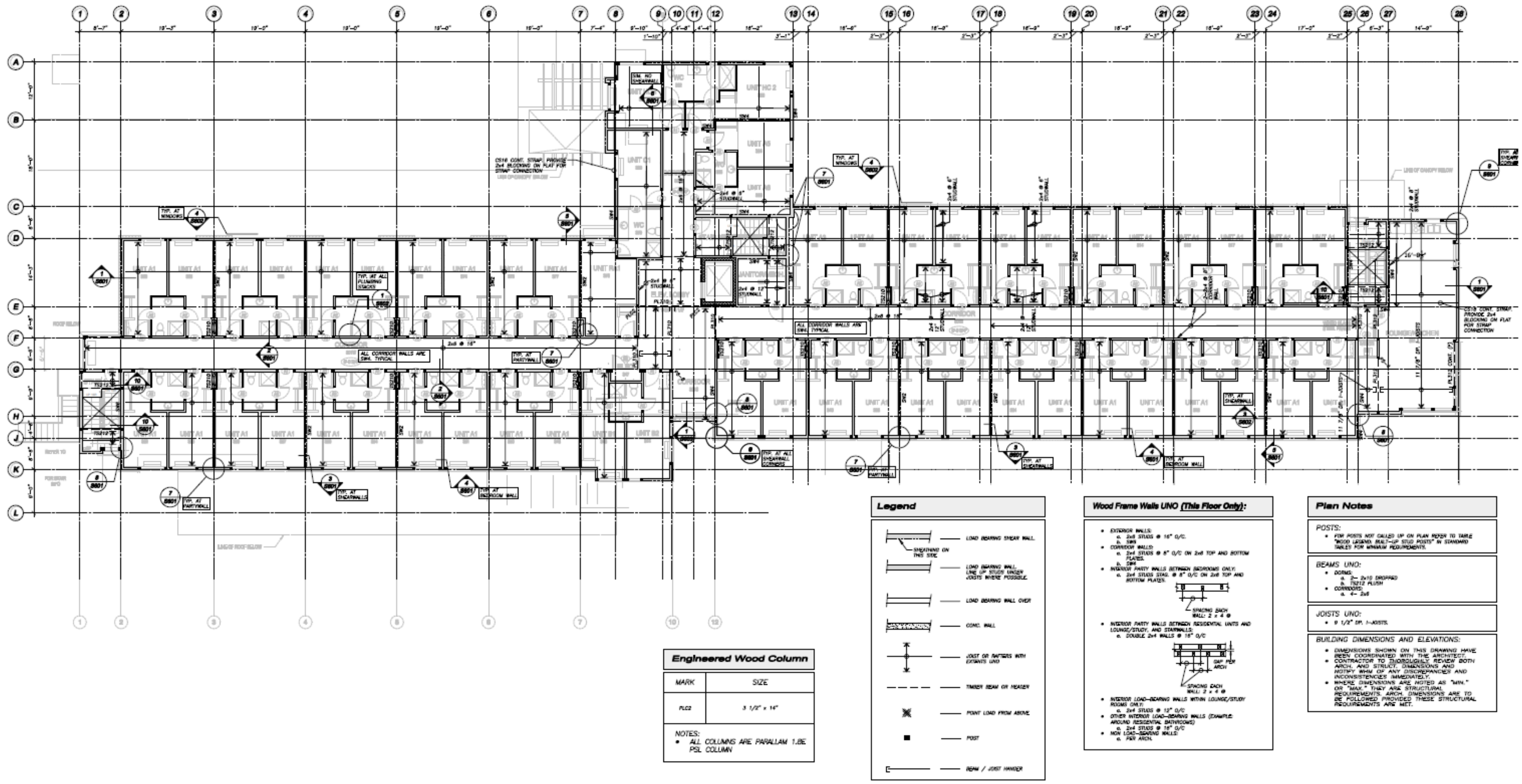

Figure B.5 Plan view of level 3

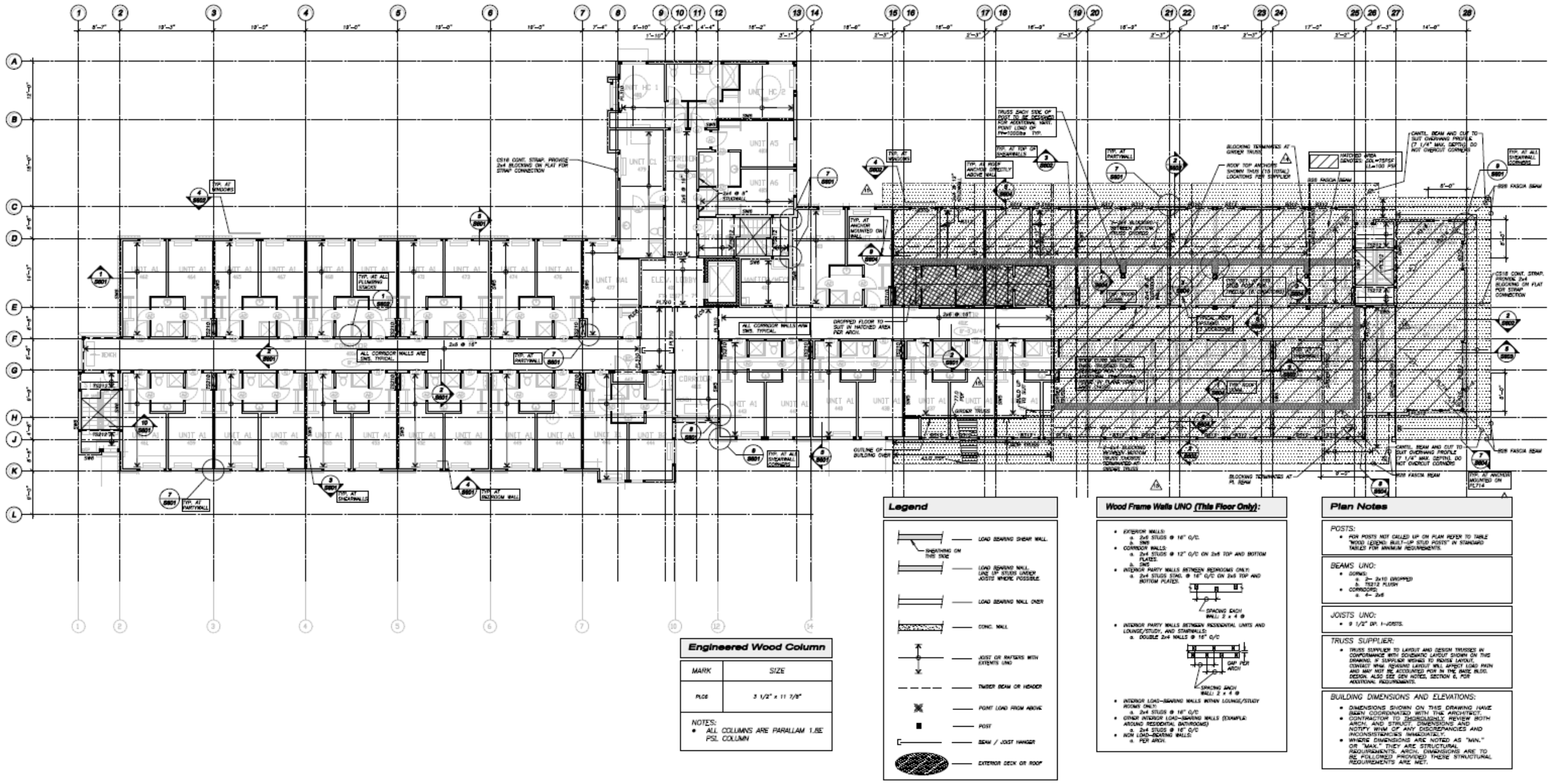

Figure B.6 Plan view of level 4

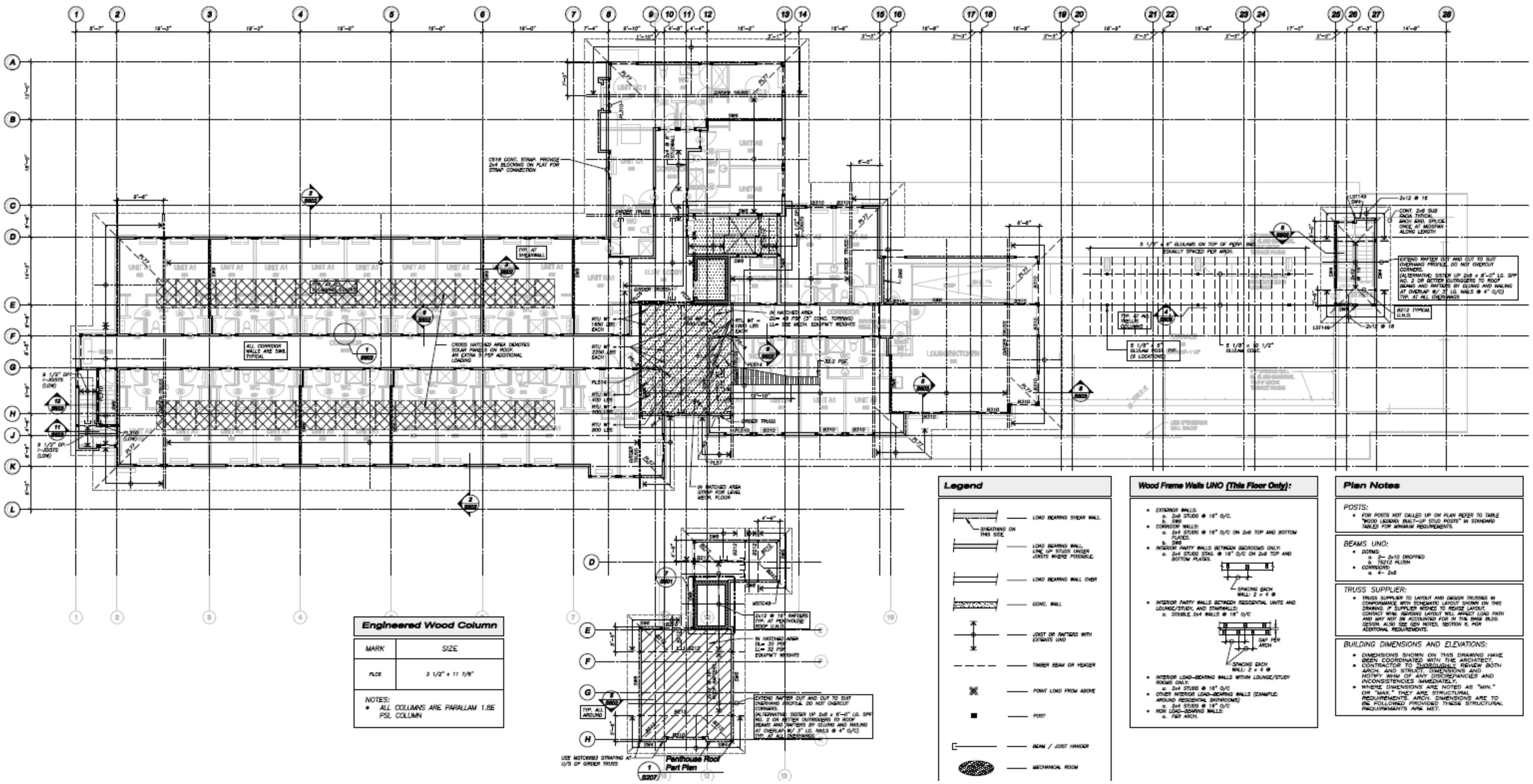

Figure B.7 Plan view of level 5

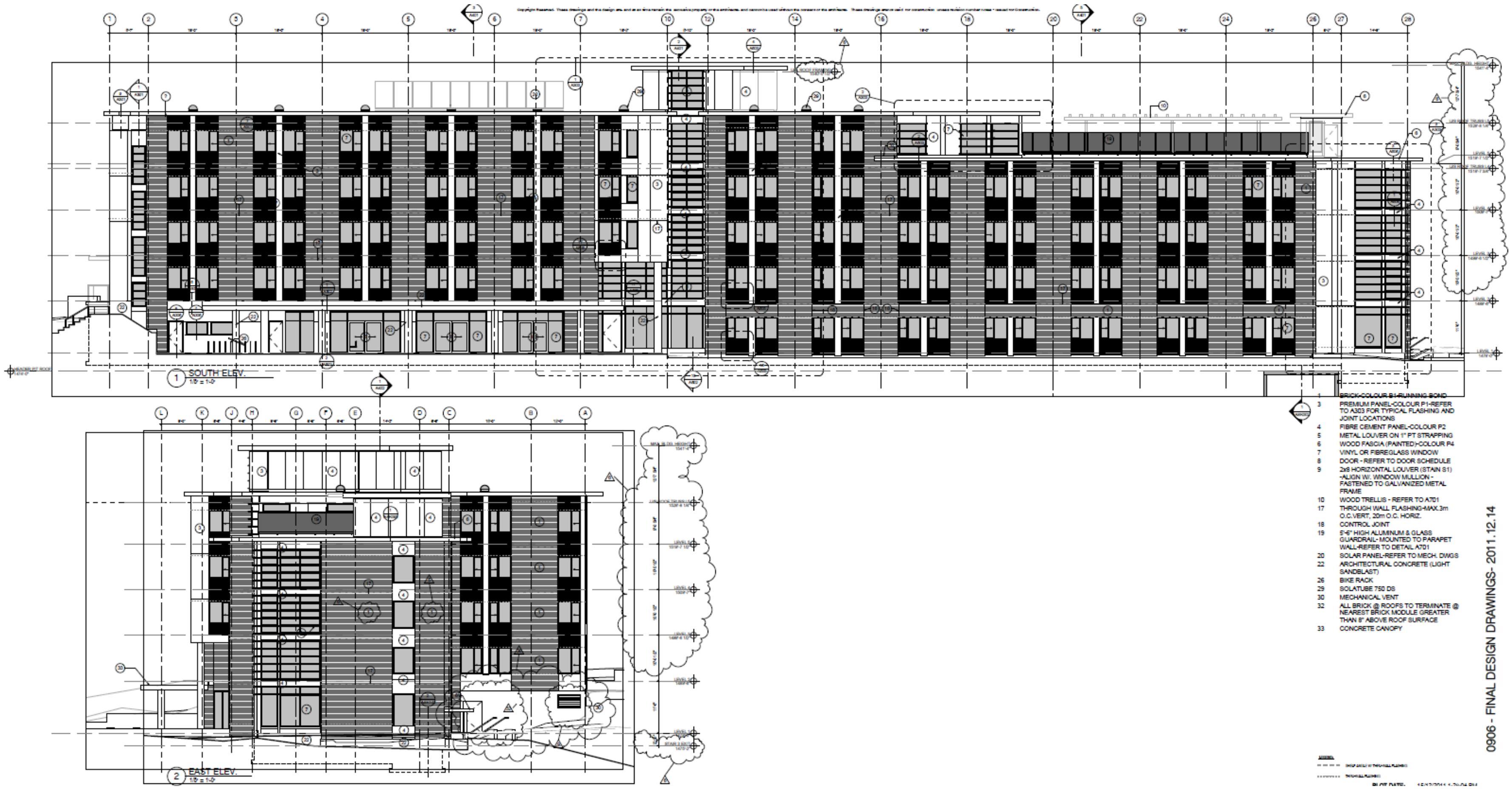

Figure B.8 Elevation view of the Purcell residence

B.2 EME building structural drawings

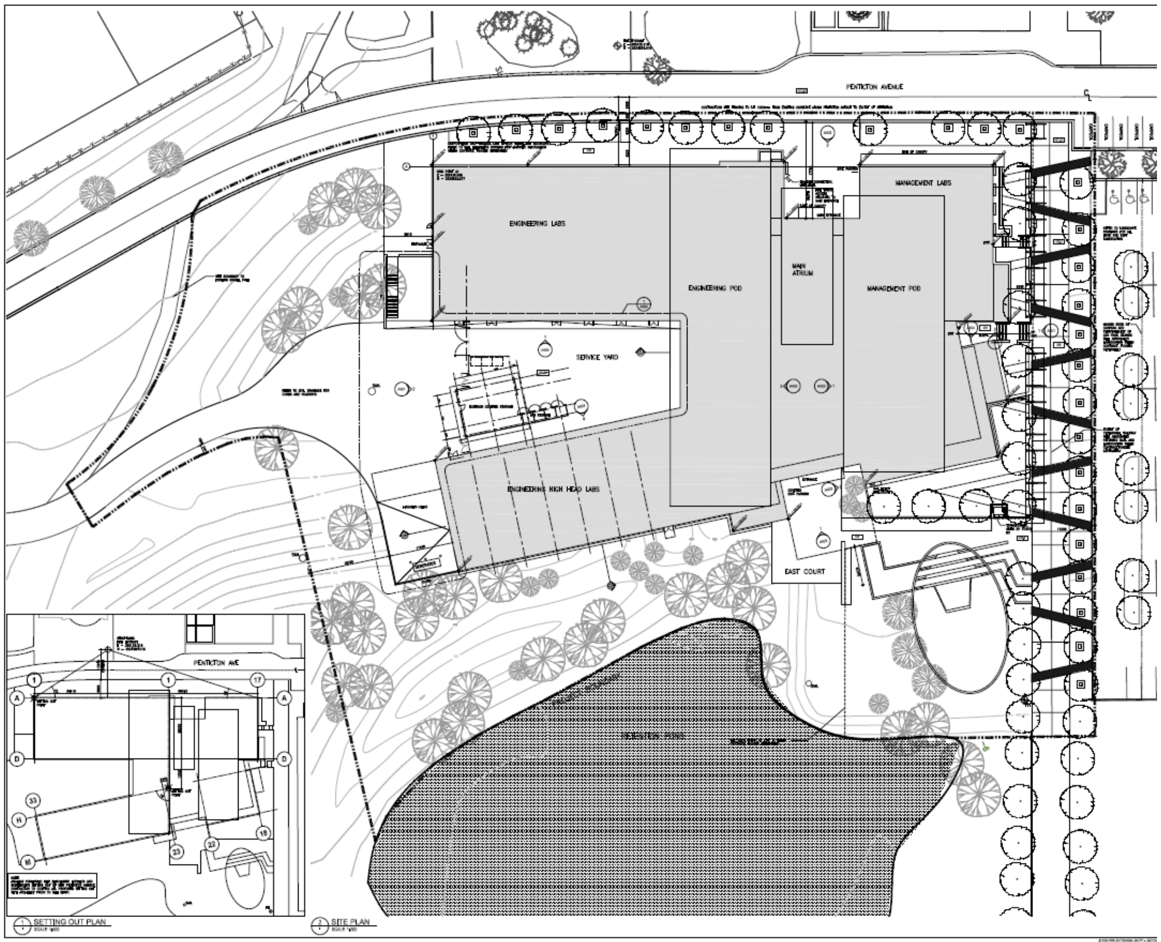

Figure B.9 Overview of EME building

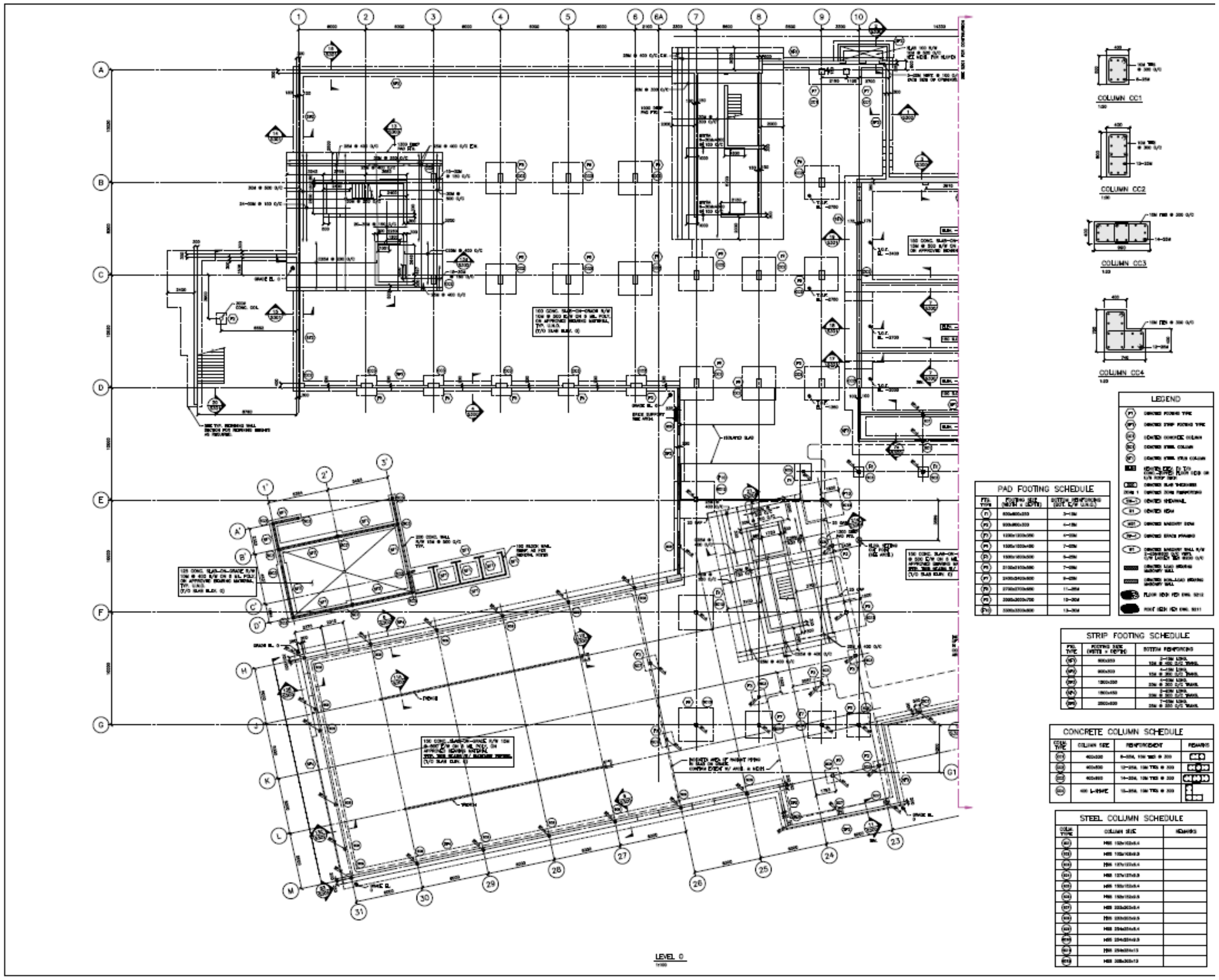

Figure B.10 Plan view of level 0A

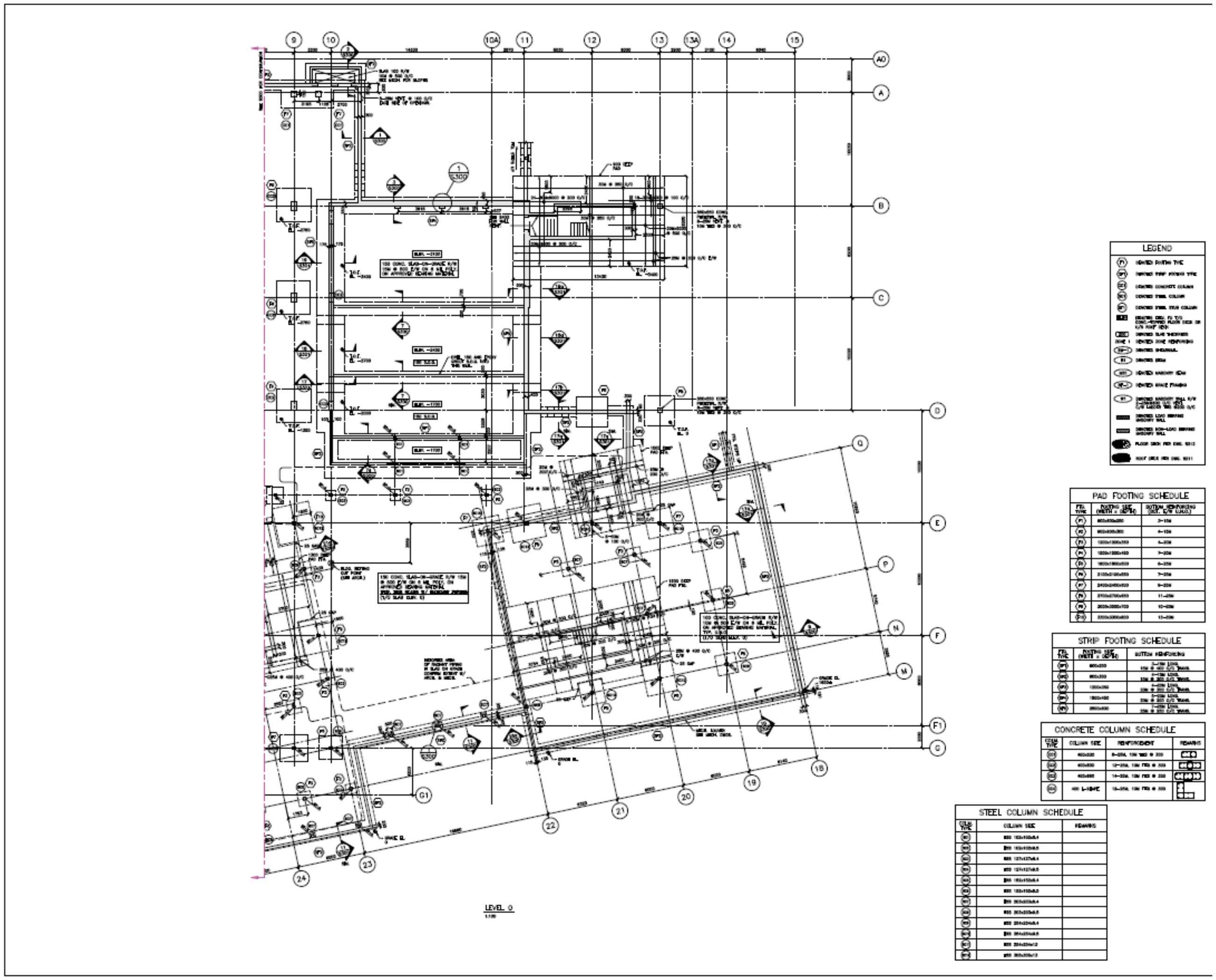

Figure B.11 Plan view of level 0B

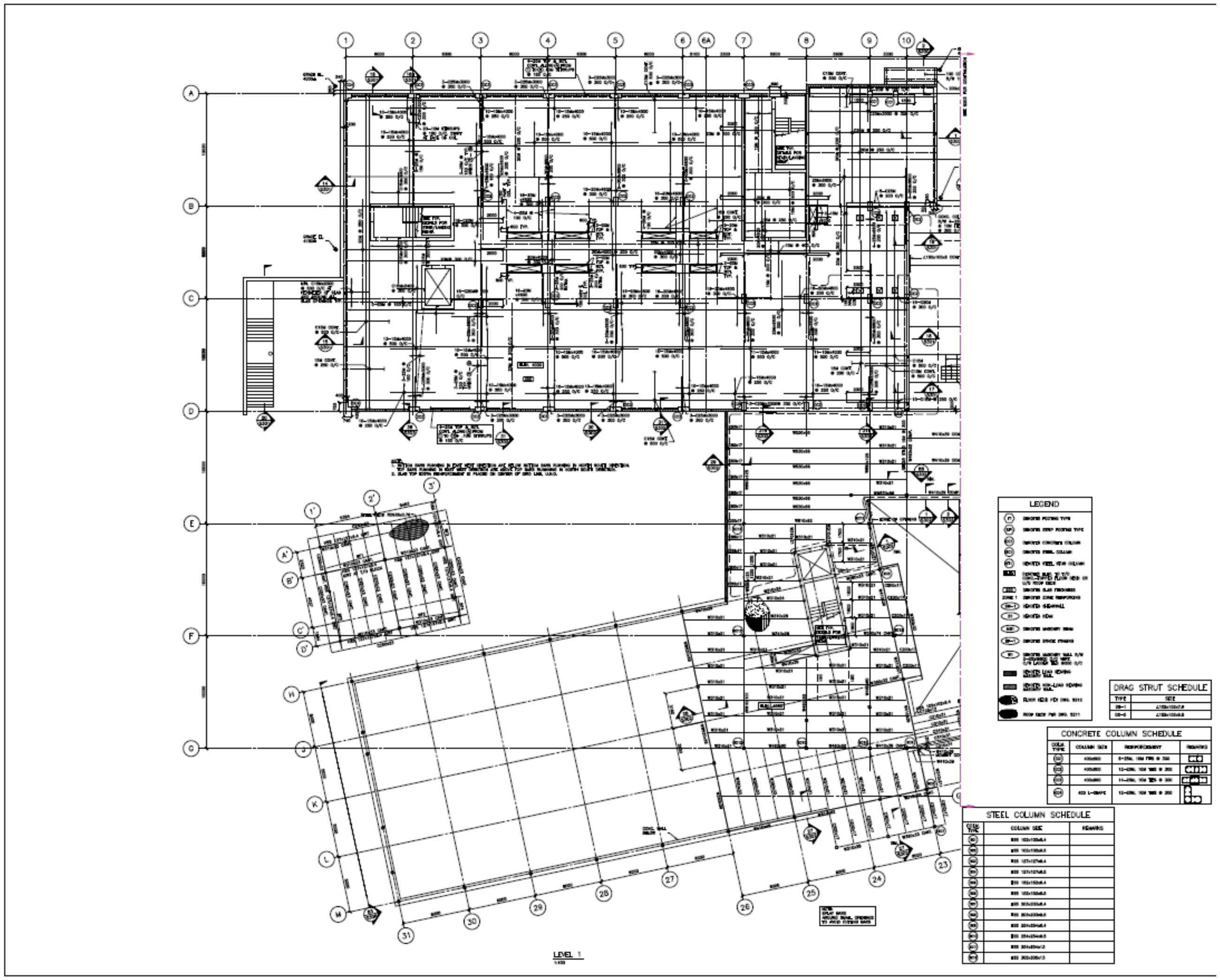

Figure B.12 Plan view of level 1A

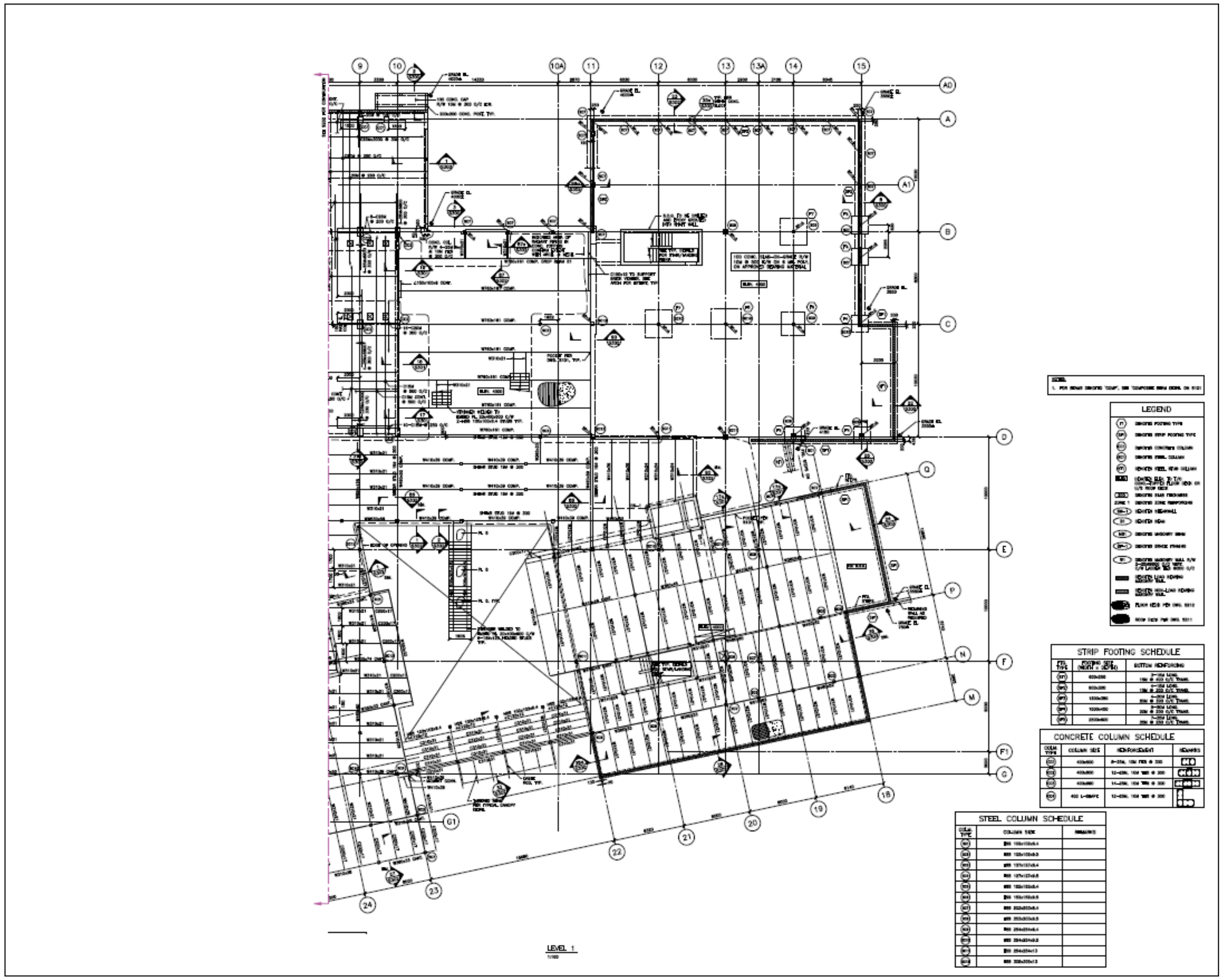

Figure B.13 Plan view of level 1B

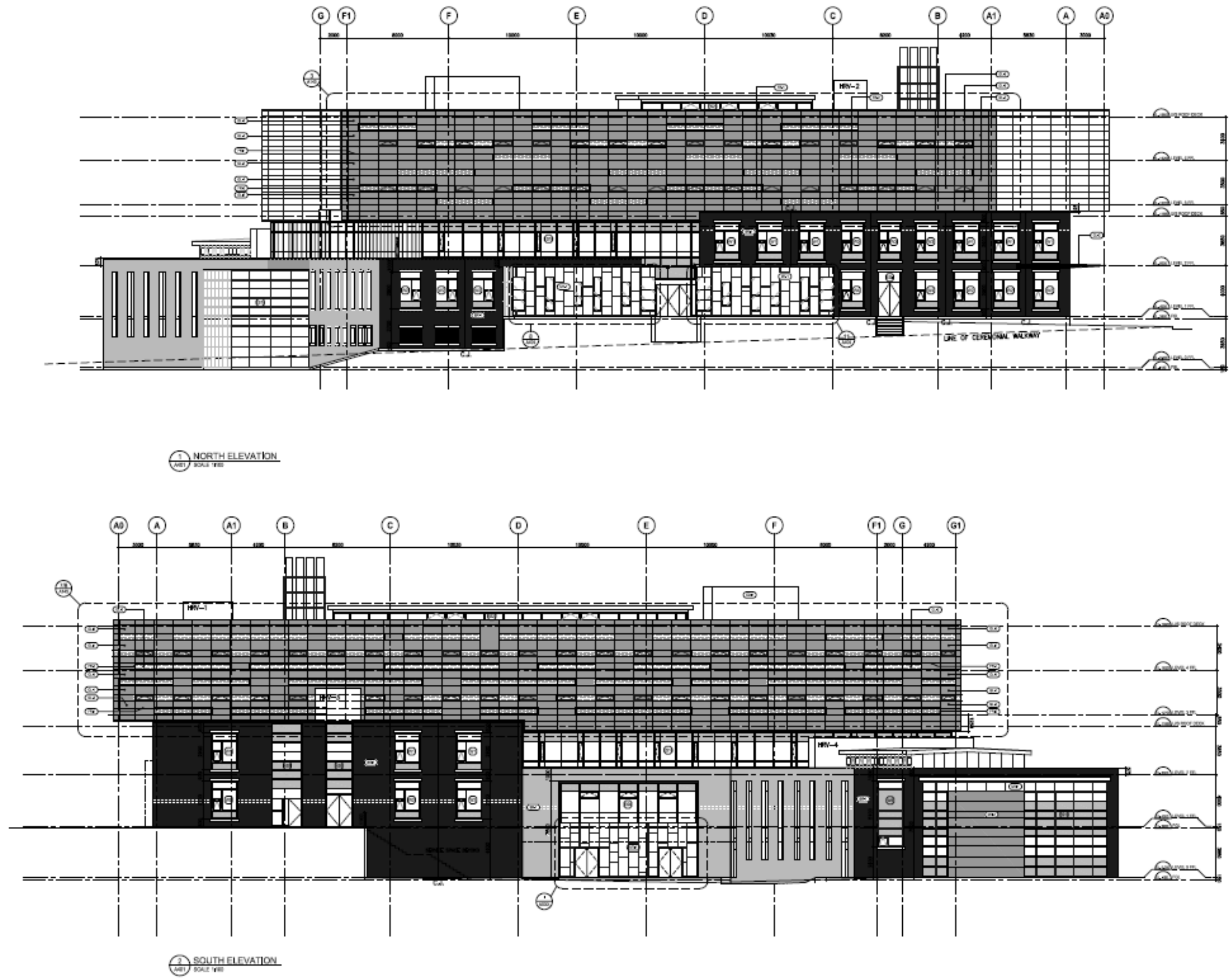

Figure B.14 Elevation view from side

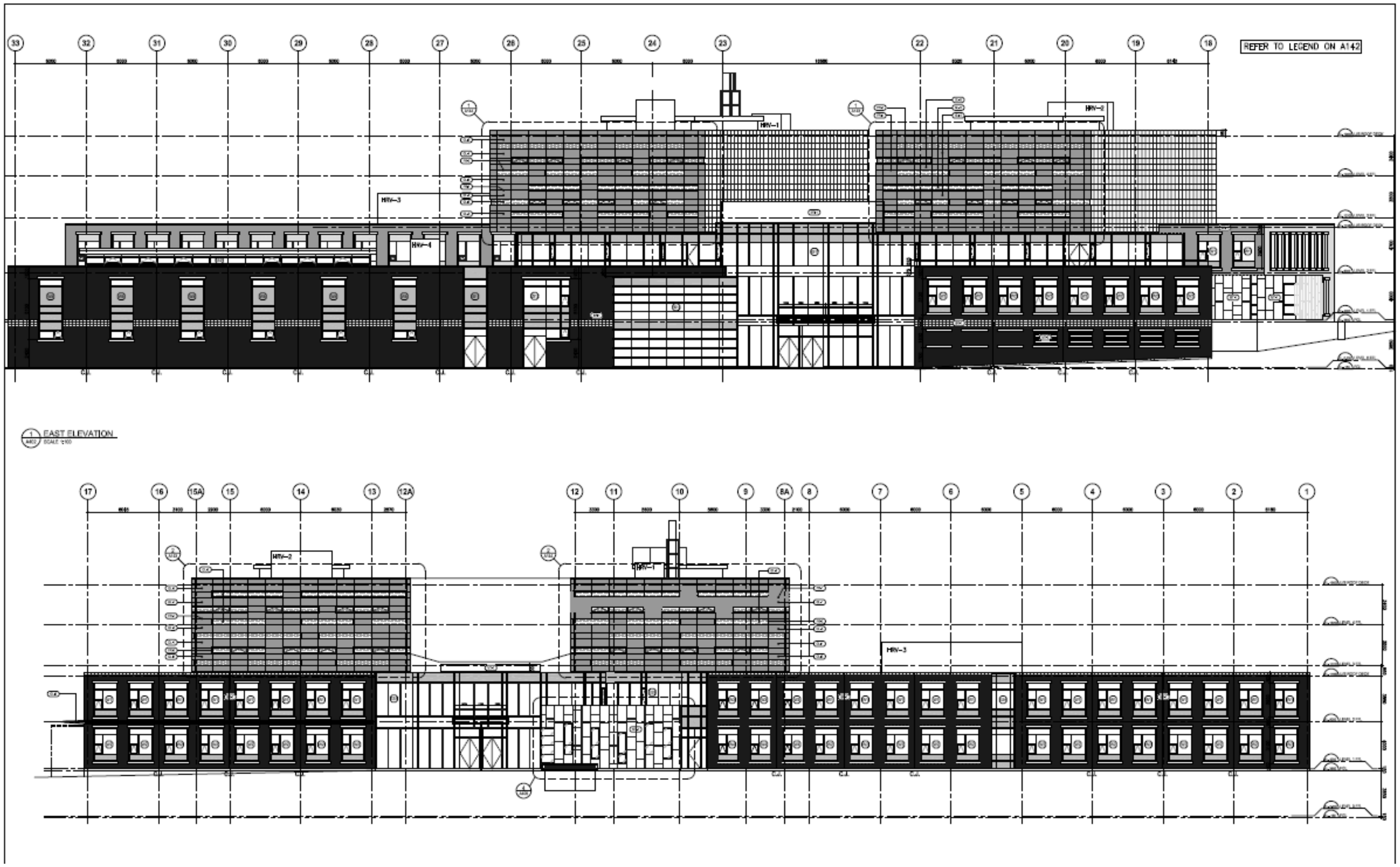

Figure B.15 elevation view from front

Appendix C Athena LCI database (Athena sustainable material institute, 2012)

Table C.1 Athena LCI database

Product	**Vintage**	**Comments**
Concrete products		
Ready Mix Concrete (3000, 4000, 9000 psi with various high volume fly ash levels (average, 25% & 35%) specified on a volume basis	CDN 2005 US 2004	• Canadian regional cement data updated from original 1993 data (concrete designs remain unchanged) • US data reflects PCA design mixes and average cement for the US • Institute report available. • US cement profile available at US LCI database (www.nrel.gov/lci)
Concrete Masonry Units (CMU) specified on a number of units basis	CDN 2005 US 2004	
Mortar - specified on a volume basis	CDN 2005 US 2004	
Steel Products -specified on a mass basis	CDN 2007 US 2007	• All product profiles reviewed and adjusted to reflect fuel use by type and mix of EAF and integrated steel production technologies per product in both Canada and the US • Institute report available. • Integrated profile for US resides in US LCI database (www.nrel.gov/lci)
Nails		
Welded wire mesh		
Screws, nut bolts		
Wide Flange sections		
Open- web joists		
Reinforcing bar		
Hollow structural steel		
Steel tubing Hot rolled sheet		
Cold rolled sheet		
Galvanized sheet		
Galvanized decking		
Galvanized studs		
Wood Products – specifed on a volume basis	CDN –various US-various	
Softwood lumber (green & kiln dried)		• Canadian regional data updated in 2009 Corrim data for US reflects PNW and SE production 2004. • Institute report available for Canadian cradle-to-gate profile. • See Corrim.org or US LCI database (www.nrel.gov/lci) for US data (2005)
Plywood		• Canadian regional (BC only) data originally developed in 1993 updated in 2006. • Resource harvesting profile updated in 2009 • Institute report available for Canadian cradle-to-gate profile.

Product	Vintage	Comments
		• Corrim data for US reflects PNW and SE production in 2004. • See Corrim.org or US LCI database (www.nrel.gov/lci) for US data
Oriented Strand board		• Canadian regional data originally developed in 1993 updated in 2006. • Resource harvesting profile updated in 2009 • Institute report available for Canadian cradle-to-gate profile.. • Corrim data for US reflects PNW and SE production in 2004. • See Corrim.org or US LCI database (www.nrel.gov/lci) for US data
Laminated Veneer Lumber		• Canadian regional data originally developed in 1993 for both LVL and PSL. • Resource harvesting profile updated in 2000. • Institute report available for Canadian cradle-to-gate profile. • Corrim data for US reflects PNW and SE production in 2004. • See Corrim.org or US LCI database (www.nrel.gov/lci) for US data (2005)
Glulam Beams		• Canadian regional data originally developed in 1993. • Resource harvesting profile updated in 2000. • Institute report available for Canadian cradle-to-gate profile. • Corrim data for US reflects PNW and SE production in 2004. • See Corrim.org or US LCI database (www.nrel.gov/lci) for US data
Wood bevel siding – 3 species	CDN -various US -various	• Canadian regional data originally developed in 2000. Cedar siding data updated in 2009 • Institute report available for Canadian cradle-to-gate profile. • US profiles based on PNW/SE lumber with Canadian transformation processes (2004) – no report available
Wood tongue and groove siding - 3 species		
Wood shiplap siding - 3 species		
Claddings	CDN -various US -various	
Sheet steel cladding residential Sheet steel cladding commercial		• Canadian and US regional data originally developed in 2000. • Institute report available for Canadian cradle-to-gate profile. • Base steel sheet values updated in 2005.
Common clay brick (modular and standard)		• Canadian clay brick data developed in 1998. Adjusted for US by substituting electricity grids and transportation distances. • Institute report available. • Canadian data Updated in 2009
Concrete brick and split faced block		• Canadian concrete brick data developed in 1998.

Product	Vintage	Comments
		• Split faced block updated in 2005. • Adjusted for US by substituting US cement profile, electricity grids and transportation distances. • Institute report available.
Stucco – over porous surface and metal mesh		• Canadian data developed in 2001. • Cement portion updated in 2005. • Adjusted for US by incorporating US cement profile and substituting electricity grids, base fuel use and transportation distances. • Institute report available.
PVC vinyl siding		• Originally developed in 1998 and updated in 2009. • PVC polymer portion to reflect new 2007 ACC data • See US LCI database (www.nrel.gov/lci) for data
Fiber Cement Siding		• Originally developed in 2009.
Natural Stone		• Developed in 2009 from a secondary data source.
Insulation and barrier products	Various for NA	
Polyethylene vapour barrier		• Originally developed in 1998 and updated in 1999. • LDPE polymer portion to reflect new 2007 ACC data • See US LCI database (www.nrel.gov/lci) for data
Air barrier		• Added in 2007 based on polypropylene profiles
Mineral Wool		• Originally developed in 1998 and updated in 2002. • Styrene polymer portion reflects new 2007 ACC data • See US LCI database (www.nrel.gov/lci)
Fiberglass		
Polystyrene XPS and EPS		
Polyisocyanurate		
Cellulose		
Polyisocyanurate		
Paint Products	Various for N. America	
Basic latex, solvent based and varnish		• Originally developed in 1998 and updated in 1999. Institute report available
Gypsum Board Products	Various for N. America	
Regular		• Originally developed in 1997. • Update and expansion planned for 2009. • Institute report available
Fire rated		
Moisture resistant		
Gypsum fiber board		
Joint compound and paper tape		
Roofing Products	Various for N. America	
3 tab shingles - organic		• Originally developed in 2000 and 2001. • Institute report available
3 tab shingles - glass		
#15 and #30 organ felt		
Type III and IV glass felt		
Mineral roll roofing		
Clay tile		• Originally developed in 1998. • Adjusted and updated for US by substituting US cement profile, electricity grids and transportation distances.
Concrete tile		

Product	Vintage	Comments
		• Institute report available
BUR organ felt based BUR glass felt based Roofing asphalt PVC Membrane EPDM membrane Modified Bitumen		• Originally developed in 2001. • Adjusted and updated for US electricity grids and transportation distances. • Institute reports available • EPDM black updated in 2009 and EPDM white added.
Windows	Various for N. America	
Wood frame PVC and PVC clad wood frame Aluminum Frame Double pane glazing, Low E coating, Argon filled		• Originally developed in 1998 and updated in 1999. • PVC polymer portion to reflect new 2007 ACC data • See US LCI database (www.nrel.gov/lci) for data. • Adding fiberglass frame in 2011 • Updated quantity take-offs in 2010 PVC and wood windows.