A PROBABILISTIC APPROACH FOR ESTIMATING ENVIRONMENTAL IMPACTS OVER THE LIFE CYCLE OF BUILDINGS

by

EDWIN ALFREDO GUERRA CASTREJÓN

B.S. Civil Engineering, Idaho State University, 2007

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
(Civil Engineering)

The University of British Columbia
(Vancouver)

October 2010

Abstract

There is increased awareness and concern regarding human activities with high environmental impacts caused by the construction, operation, maintenance and decommissioning of the built environment. The work presented in this thesis helps predict holistically the environmental impact indicators of different building design options. A probabilistic framework, applicable to multiple building function types, is proposed to estimate the environmental metrics of energy, water and global warming potential. The environmental impact indicators are studied at varying resolutions of data quality. The proposed framework differs from alternate tools by explicitly accounting for uncertainty through the use of random variables in its models. The modeling approach emphasizes greater transparency of the environmental impact intensity values that relate known information about the building, such as material quantities, with respective environmental impacts. Explicit environmental impact models are presented for each of the building's life cycle phases, including extraction, manufacture, on-site construction, operation, maintenance, and end of life. The methodology is then demonstrated by analyzing a sample residence in Ontario. The environmental impacts associated with the entire life cycle of the building are reported and possible improvements to the methodology are identified. The ability to analyze the probability of exceeding an environmental impact threshold is a feature of this work that is useful in the refinement of environmental performance rating systems. The general lack of public information about the environmental impact of the manufacturing of building components in North America, as well as uncertainty about component replacement frequency and the building service life continue to pose a challenge for environmental impact analysis. However, this thesis presents a new probabilistic framework in which this uncertainty is explicitly identified and addressed.

Table of Contents

Abstract ..... **ii**
Table of Contents ..... **iii**
List of Tables ..... **v**
List of Figures ..... **vii**
Acknowledgements ..... **viii**
Dedication ..... **ix**
1 Introduction **1**
1.1 Overview 1
1.2 Motivation 3
1.3 Research Objectives 4
1.4 Scope 5
2 Definitions and Tools for the Study of the Buildings **8**
2.1 History and Definition of Sustainability 8
2.2 Defining the Life Cycle of a Building 13
2.3 Frameworks of Analysis of Buildings 19
2.3.1 Building Rating Systems 20
2.3.2 Life Cycle Assessment 24
2.3.3 Software Tools 37
2.4 Environmental Impact Indicators 40
2.4.1 Energy 40
2.4.2 Water Usage 41
2.4.3 Global Warming Potential 42
3 Previous Environmental Impact Studies **45**
3.1 Life Cycle Studies of Buildings 45
3.2 Uncertainty in Life Cycle Assessment 55
4 Environmental Impact Models **58**
4.1 Analysis Framework 58
4.1.1 Probabilistic Models 60
4.1.2 Rt Software 64
4.1.3 Life Cycle Model Methodology 65
4.1.4 Simplified Building Life Cycle 66
4.1.5 Sources of Data 69
4.2 Environmental Impact Model Library 74
4.2.1 Energy Building Models - Fine Detail 75
4.2.1.1 Extraction and Manufacturing Phase 76
4.2.1.2 On-Site Construction Phase 78
4.2.1.3 Building Operation Phase 80
4.2.1.4 Maintenance Phase 81
4.2.1.5 End of Life Phase 84
4.2.2 Energy Building Models - Coarse Detail 85

4.2.2.1 Pre-Use Phase 85
4.2.2.2 Operation Phase 86
4.2.2.3 End of Life phase 87
4.2.3 Water Usage Building Models – Fine Detail 88
4.2.3.1 Extraction and Manufacture Phase 89
4.2.3.2 On-Site Construction Phase 90
4.2.3.3 Operation Phase 90
4.2.3.4 Maintenance and End of Life Phases 92
4.2.4 Water Usage Building Models - Coarse Detail 92
4.2.4.1 Entire Life Cycle 92
4.2.5 Global Warming Potential – Fine Detail 93
4.2.5.1 Extraction and Manufacture Phase 93
4.2.5.2 On-Site Construction Phase 94
4.2.5.3 Operation Phase 95
4.2.5.4 End of Life Phase 95
4.2.6 Global Warming Potential – Coarse Detail 96
4.2.6.1 Entire Life Cycle 96
5 Example 97
5.1 Assumptions 97
5.2 Detailed Model Inputs 98
5.3 Results 105
6 Conclusion 111
6.1 Summary 111
6.2 Future Research 112
References 116

List of Tables

Table 1.1 Life cycle environmental impact of buildings research scope 7
Table 2.1 Environmental considerations by building life cycle stage 19
Table 2.2 Rating system category comparison (from International Living Building Institute 2010; Building Research Establishment; US Green Building Council; Japan Sustainable Building Consortium 2006) 22
Table 2.3 How LCA and LCC differ in purpose and approach (Norris 2001) 25
Table 2.4 Process LCA and Input-Output LCA comparison (from Sharrard 2007) 31
Table 2.5 Cause-effect chain of impact categories (from Bare et al. 2002) 35
Table 2.6 Greenhouse gases, atmospheric lifetimes and weights for a 100-year time horizon 42
Table 4.1 Sources for energy, water and emissions data relating to extraction and manufacture of building materials 69
Table 4.2 Sources for energy data during the operation phase of a building 71
Table 4.3 Sources useful in determining transportation air emissions during the building life cycle 73
Table 4.4 Sources for maintenance and life expectancies of building products 73
Table 4.5 Energy model for extraction and manufacture stage, fine detail 76
Table 4.6 Sample energy intensity values, i_p, and waste factors for building materials 77
Table 4.7 Example energy and GWP intensities of freight transport for year 2007 in Canada 78
Table 4.8 Energy model for on-site construction stage, fine detail 78
Table 4.9 Sample passenger transportation intensity values in British Columbia (Poudenx and Merida 2007) 79
Table 4.10 Energy model for building operation stage, fine detail 80
Table 4.11 Energy model for building maintenance stage, fine detail 81
Table 4.12 Life spans of materials used in construction 82
Table 4.13 End of life phase energy model, fine detail 84
Table 4.14 Energy model for pre-use phase, coarse detail 86
Table 4.15 Energy model for operation, coarse detail 86
Table 4.16 Energy model for end of life phase, coarse detail 87
Table 4.17 Water model for extraction and manufacturing phase, fine detail 89
Table 4.18 Water usage during on-site construction, fine detail 90
Table 4.19 Water usage during operation, fine detail 90
Table 4.20 Fixture and use information per day (adapted from Canada Green Building Council 2004) 92
Table 4.21 Entire life cycle water usage, coarse detail 93
Table 4.22 Global warming potential for extraction and manufacture, fine detail 94
Table 4.23 Global warming potential for on-site construction, fine detail 94
Table 4.24 Global warming potential for building operation, fine detail 95
Table 4.25 Global warming potential for end of life, fine detail 95
Table 4.26 Global warming potential for entire life cycle, coarse detail 96
Table 5.1 Original material quantity conversion assumptions 99
Table 5.2 Quantity and intensity values used as Rt input 100
Table 5.3 Assumed transportation distances 101
Table 5.4 Construction related inputs 102
Table 5.5 Annual energy demand breakdown 103

Table 5.6 Operation related inputs 103
Table 5.7 Gamma importance measures 106
Table 5.8 Summary results table 108

List of Figures

Figure 1.1 Environmental impacts of buildings in Canada (CEC 2008) 3
Figure 1.2 Unified reliability framework.. 6
Figure 2.1 Visual representation of the Triple Bottom Line interpretation of sustainability 10
Figure 2.2 'Deep green' sustainable development interpretation (Adapted from Gibson 2001)... 12
Figure 2.3 Life cycle of a building.. 14
Figure 2.4 Example of a residential building energy system... 16
Figure 2.5 USGBC LEED v2.2 and v3.0 for New Construction & Major Renovations points ... 23
Figure 2.6 Stages in LCA (Canadian Standards Association 2006a) 26
Figure 4.1 Conceptual probabilistic model description 62
Figure 4.2 Probabilistic environmental impact model and its place within overall framework ... 62
Figure 4.3 Screenshot of Rt software... 65
Figure 4.4 Simplified building life cycle energy usage 67
Figure 5.1 Life cycle energy usage for example residence.. 105
Figure 5.2 Life cycle water usage for example residence.. 107
Figure 5.3 Life cycle GWP for example residence.. 108

Acknowledgements

I recognize not everyone has the privilege of pursuing a research topic that is in line with their personal passion. For this reason, I consider myself extremely fortunate to have sought such a multifaceted, rich and challenging topic for my thesis. I am thankful beyond words to everyone who has helped me reach this milestone: from my family who was supportive from the very earliest days of my life to all the amazing professors and students who provided encouragement and direction.

My most sincere appreciation goes to my supervisor Dr. Terje Haukaas who was always enthusiastic and supportive of my work and to Dr. Susan Nesbit who is doing great things at UBC to help form the socially and environmentally responsible engineers of tomorrow. Many thanks to the UBC Emerging Green Builders group, Ivan, Stefan, Morghain, Ross, Rob and Jay. The group provided me with a creative outlet to explore and understand the green building industry in Vancouver and become energized by the curiosity of other students. Thanks to the Infrastructure Risk research team, Dr. Foschi, Dr. Elwood, Dr. Chang, Alejandro, Shahrzad, Mojtaba, Karthick and Majid for all of their useful questions and comments.

I would also like to thank my family, specially my parents and brother, who provided me with great tools to pursue all my interests and let me grow to reach my full potential. Finally, thanks to my wife Nicole, my soul mate, for her patience with my endless readings and occasional grumpiness. Thank you for always motivating me to do my absolute best.

This work was supported through the Infrastructure Risk project funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) under the Strategic Project Grant STPGP 336498-06.

To Nicole

1 Introduction

We do not inherit the Earth from our Ancestors,

we borrow it from our Children.

Ancient Native American Proverb

1.1 Overview

The objective of this thesis is to present a framework for incorporating environmental considerations into decisions that are normally influenced by structural and civil engineers. It is envisioned that the structural engineer will augment the traditional considerations of structural safety and cost with considerations of environmental impacts. Typically, a structural design comprises important decisions regarding type and amount of construction material to resist the loads that it may experience in the future. The materials selected also have significant environmental consequences. For example, the selection of reinforced concrete instead of wood has environmental implications, which are worthy of consideration, in addition to the traditional consideration of strength and stiffness.

The methodology proposed in this thesis provides a procedure to quantify the environmental impacts of the built environment by studying and proposing models for each of the life cycle phases of a building. A probabilistic approach is adopted, in which the unavoidable uncertainties in the environmental impact predictions are addressed. The environmental impacts estimated include energy, water use and global warming potential (GWP). A primary aspiration is to enhance the classical structural reliability approach, epitomized by Sanchez-Silva and Rosowsky

(2008) who optimized structural designs under consideration of social and economic indicators for different earthquake-prone countries. However, Sanchez-Silva and Rosowsky were hesitant to include environmental impact indicators. In the words of the authors, "Although environmental aspects are important and should be included as part of any comprehensive analysis, they will not be considered in the present paper since their quantification is still a matter of great debate."

In this thesis, the structural reliability methodology that was developed in a comprehensive effort by the global structural engineering community in the 1970's and 80's to address the safety of load-bearing structures is extended. In the classical structural reliability analysis, "limit-states" are used to identify undesirable structural response. One example is a limit-state function that specifies that the loading stress should not exceed the yield stress capacity of the material. The purpose of structural reliability analysis is to compute the probability that the limit-state will be exceeded, followed by an assessment of whether that probability is acceptable. This thesis amends this approach by introducing limit-states for environmental impacts. The intention is to specify limit-states for energy usage, water usage and GWP in order to include environmental sustainability in modern structural designs. A particular novelty in this thesis is the candid consideration of uncertainties. Similar to what is done in classical structural reliability analysis, uncertainties in the estimation of energy usage, water usage and GWP are characterized by probabilistic means. Input parameters to the environmental impact models are given as random variables, and the model uncertainty (potential errors in model form or missing parameters) is explicitly accounted for.

1.2 Motivation

The construction industry is responsible for a significant proportion of environmental damage. Buildings alone are responsible for roughly half of all energy consumption in Canada (Natural Resources Canada 2009). In North America, buildings utilize 5-12% of potable water and create 20-25% of the landfill waste (CEC 2008). Figure 1.1 reports some of the environmental impacts that are attributed to buildings in Canada according to the Commission for Environmental Cooperation. Buildings are shown to consume significant amount of natural resources, water and energy while also producing emissions, in the form of greenhouse gases and landfill waste. Each of these demands creates environmental impacts that range from habitat destruction and fragmentation to various forms of pollution of air, land and water (Cuddihy et al. 2005).

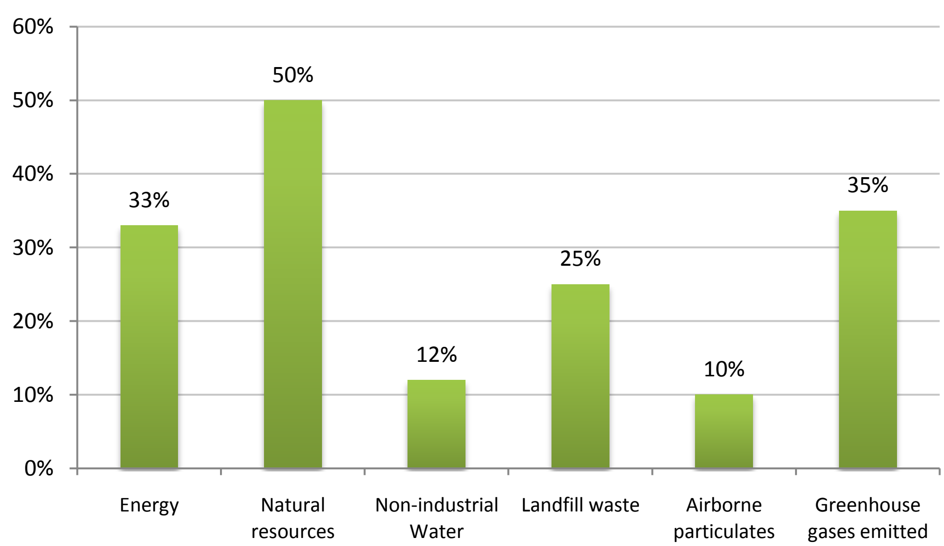

Figure 1.1 Environmental impacts of buildings in Canada (CEC 2008)

The Green Building movement has grown as a response to this situation by offering innovation through the design of “green” buildings. These buildings help reduce environmental impacts by using less energy and resources, producing less waste, providing healthier environments to building users and leveraging interdisciplinary design teams (CEC 2008; Yudelson 2009). The Green Building movement however, is currently largely based on best management practices and other qualitative-focused guidelines. Therefore, while the concern for better environmental practices has increased, the quantification of environmental impacts is still an emerging field (Graedel and Allenby 2009). The present work, which can account for uncertainty by producing responses in the form of statistical distributions, is a valuable tool that can inform decisions beyond traditional deterministic analyses.

1.3 Research Objectives

This research will address the following questions and objectives:

- To document and summarize previous studies of the environmental impact of the built environment with a particular focus on structural engineering.
- To formulate a general framework to include environmental impacts in design decisions in structural engineering. This framework includes:
    - Probabilistic environmental impact models for estimating life cycle energy usage, water usage and GWP.
    - Reliability analysis carried out to address environmental limit states.
- To create and implement on the computer the probabilistic environmental consequence models.
- To demonstrate the use of the models through the calculation of an example and formulate suggestions for future improvements.

- To indentify the possible directions of future research in quantifying the environmental impact of buildings applicable to structural engineers.

In summary, the purpose of this research is to set up a probabilistic framework that allows designers such as structural engineers to estimate environmental impact incurred through the entire life cycle of buildings.

1.4 Scope

The present study may be viewed as the development of a framework of probabilistic models. In essence, the information from a "building information model" and other probabilistic models is used to develop a consequence model: a model that in this case computes environmental impacts. The inputs to each probabilistic model are continuous random variables or decision variables that are propagated through the probabilistic models. The output is the probability of exceeding a prescribed limit state, for example, an environmental impact threshold. The "failure" probability, as well as the useful by-products of the reliability analysis, i.e. importance vectors, are intended to assist decision makers in making better decisions that include consideration of environmental concerns.

As mentioned earlier, the model implementation is well suited for incorporation into the classical reliability methodology. One modern software application for this purpose is developed at the University of British Columbia and named Rt (Mahsuli and Haukaas 2009). Figure 1.2 presents the overall framework for an earthquake engineering application as outlined by Haukaas (2008). The analysis is performed by generating individual realizations for random variables that are used as inputs in the different models. Some of these models create output that is used as input in subsequent models as shown. The diagram shown describes the generation of an earthquake hazard that is propagated through infrastructure models that produce a response, which creates damage, prompts a repair action, and is eventually translated to a cost model. The models developed in this thesis will serve as autonomous consequence models for estimating the environmental impacts of the life cycle of a building and are at present not connected to other models.

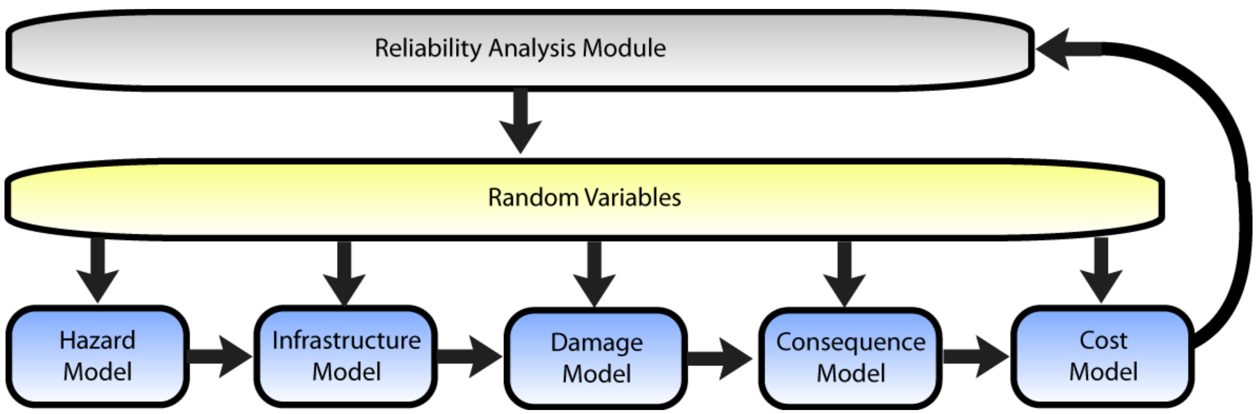

Figure 1.2 Unified reliability framework

The holistic study of environmental impacts in the built environment is a problem that contains several components. Table 1.1 summarizes the primary axes that define the scope of the models that are explored in this thesis. The three axes are: environmental impacts, life cycle phases, and resolution of the input. The environmental impact models quantify energy use, water use, and GWP over the life cycle of a building. These indicators are used to reveal the links between designer choices and environmental impact performance of a building. The different life cycle phases of extraction and manufacture, on-site construction, operation, maintenance and end of life, provide a comprehensive overview of the environmental impacts. Additionally, different models with varying degrees of input data resolution are proposed. Models that can accommodate lower degrees of data resolution are particularly useful for carrying out regional analyses where the collection of detailed information about each building is impractical.

Table 1.1 Life cycle environmental impact of buildings research scope

Impact	Life Cycle Phase	Scale	Detail
Energy (J) GWP (kg CO_2e) Water (L)	Extraction & Manufacture On-site construction Operation Maintenance End of life	Building Regional	Coarse Fine

The proposed framework allows the future incorporation of hazard information into the life cycle calculations. The earthquake hazard is one example. Although outside the scope of this thesis, the environmental impact of repair of earthquake damage can be included. This can have significant impact on design decisions, because designs that prevent earthquake damage will also prevent the environmental impacts associated with the repair. Specifically, earthquake damage may prompt the premature replacement of building materials such as flooring, glass or siding. In more extreme scenarios, the repair or replacement could involve a significant portion of a building or its entirety. All of these renovation and repair actions have pre-use (extraction, manufacture, transportation, installation) and post-use (end of life) environmental impacts. In certain extreme events, such as hurricanes, earthquakes, fires or floods, environmental impacts could be significant and should be considered in future studies of the life cycle environmental sustainability of the built environment. The proposed framework will be able to accommodate such extensions by having the capability to link to other models in the Rt software.

2 Definitions and Tools for the Study of the Buildings

The objective of this chapter is to provide an overview of the origins of the concerns for the natural environment and how these concerns have shaped the way that the environmental impact of buildings are estimated. A particular focus is on understanding what tools have been proposed to quantify the environmental impact of buildings, which impacts are traditionally considered, how the tools differ in their approaches and how they calculate different impacts.

The chapter begins by providing a brief overview of sustainability. It then introduces several tools to analyze environmental impacts of the built environment. Finally, an overview is provided of the environmental impact indicators that will be studied in this thesis.

2.1 History and Definition of Sustainability

One of the most often quoted occurrences of the concept of sustainability appears in the Brundtland Commission's report titled *Our Common Future* in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). The original term used was "sustainable development" which is now commonly used interchangeably with "sustainability."

The Brundtland Commission's recommendations were threefold:

- to protect the environment through conservation and preservation of natural resources;
- to promote responsible economic growth that prevents further deterioration of the environment; and
- to support social equity by bringing forward the benefits to all sectors of society.

Although the concept of sustainability may be traced back conceptually to much earlier history, the Brundtland definition is important because it was formulated with global consensus and because it recognized that economic growth alone may not be sufficient to advance a nation's interests. The Brundtland concept of sustainability is sometimes separated into two main ideas: intragenerational and intergenerational equity (George 1999). The former refers to a social focus where it is desired that citizens live in a fair society with unhindered opportunity exemplified by equity within a community. The latter emphasizes the goal of securing resources and an environmental quality that will maintain an equivalent or increased lifestyle and wellbeing for future generations.

The World Commission on Environment and Development's effort was followed by the UN Conference on Environment and Development, the 'Earth Summit I' at Rio de Janeiro, Brazil in 1992. Prepared with the goal to develop a sustainable international community, this conference yielded five agreements:

- the Convention on Biological Diversity;
- the Framework Convention on Climate Change;
- the Rio Declaration on Environment and Development;
- Principles for Sustainable Management of Forests; and the
- Agenda 21.

The Program of Action for Sustainable Development in Agenda 21 provides governments with tools on how to apply the principles of sustainable development. Composed of 40 chapters, Agenda 21 is broad, covering conservation of biological diversity, strengthening of governmental organizations, roles of women, children and youth in sustainability, and providing information for decision-making (United Nations Conference on Environment and Development 1993). These early milestones have shaped today's view of sustainability.

Current definitions of sustainability and sustainable development, although slightly varied, still center among the three interconnected pillars stemming from the Brundtland report: the environmental, economical, and social equality. For example, at the University of British Columbia, the Centre for Interactive Research on Sustainability (2008) defines sustainability as "…a reconciliation of the *ecological imperative* to stay within the carrying capacity of the planet, the *economic imperative* to provide an adequate standard of living for all, and the *social imperative* to develop forms of governance that promote the values people want to live by." In the literature this definition is commonly referred to as the Triple Bottom Line and is presented visually in Figure 2.1. Each domain, environmental, economic and social, is represented by three circles that overlap with each other. Actions that constructively advance all three outcomes, an event which could be visualized as the intersection of the three circles, represent solutions that are sustainable according to a Triple Bottom Line approach (Elkington 1998).

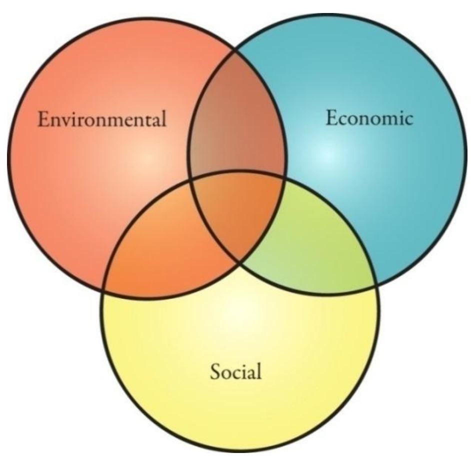

Figure 2.1 Visual representation of the Triple Bottom Line interpretation of sustainability

The strength of the Triple Bottom Line is its conceptual simplicity and its ability to fit within current established branches of government. However, the biggest critique of the Triple Bottom Line approach is that it is hard to quantify, track and measure in practical situations (Norman and MacDonald 2004). Another point of contention is whether or not the benefits from each branch are interchangeable. It is concluded that the Triple Bottom Line approach represents a simple and idealized way to visualize sustainability.

Alternate definitions of sustainability have been proposed. Some of these focus primarily on the environment. An example from the field of Ecological Economics is the “deep green” or eco-centric interpretation of sustainable development as shown in Figure 2.2. By placing society and the economy inside of the ecology circle, it attempts to emphasize the fact that any deterioration of the environment undermines other aspects of human activity (our society and our economy). Therefore, it rearranges the relative importance of the environment, society and economy. On the other hand, a “pale green” or anthropocentric interpretation of sustainable development allows trade-offs between the three imperatives. Advocates of pale green decisions argue that economic and social benefit at the expense of some environmental impact is sometimes acceptable. That is, the utility derived from economic, social and environmental capital is interchangeable (Hecht 2005). While proponents of a deep green approach suggest internalizing the environmental costs of products, few are able to reach a consensus on what these costs should be and how they should be calculated (Costanza et al. 1997a).

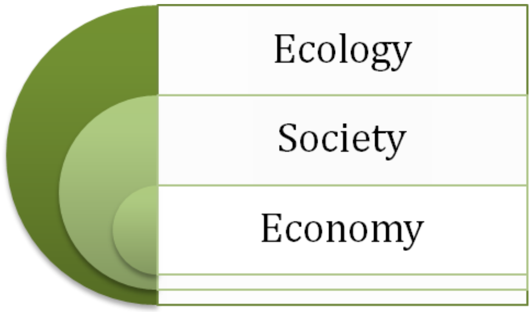

Figure 2.2 'Deep green' sustainable development interpretation (Adapted from Gibson 2001)

Herman Daly (1991) suggests three conditions to meet a “strong” environmental sustainability:

- Rates of use of renewable resources do not exceed replacement rates;
- Rates of use of non-renewable resources do not exceed rates of development of renewable substitutes;
- Rates of pollution emissions do not exceed the assimilative capacity of the environment.

Similarly, Alberti (1996) points out that a general agreement about sustainability is that there should be a constant natural stock to support future populations. However, Alberti acknowledges that there are large uncertainties associated with defining realistic numbers for the assimilative and regenerative capacities of different ecological systems on Earth.

Traditional economics does not assign a value to services provided by nature such as trees, which capture carbon dioxide, filter water, create a microclimate, provide habitat, stabilize soil, and improve storm water infiltration, and provide other vital services. In 1997, a few ecological economists put together an estimate of the value of the entire biosphere at an average of US$33 trillion per year, which was 1.8 times the global gross natural product (Costanza et al. 1997b). As expected, most of the value of the biosphere falls outside the market and requires non-traditional valuation techniques such as “willingness to pay” where surveys are developed to ask people to estimate how much they are willing to pay for a service, such as the amenity of going hiking in the wilderness (Farber et al. 2002).

At its heart, sustainability is about recognizing economic, environmental and social limits and understanding them to ensure a stable quality of life for generations to come. While some approaches (Rees 2003) attempt to establish what these limits are in a quantifiable way, others (Robèrt 2000) simply attempt to understand current practice and determine opportunities for reducing or minimizing impacts on the natural environment. Sustainability attempts to make evident the complex interrelationships between a desired future and the decisions designers can influence. The scope of this thesis is most related to the ecological aspects of sustainability and will not directly address its economic or social aspects.

The application of sustainability concepts may require the translation of "world-view" definitions into practical design objectives through quantitative methodologies like the one proposed in this thesis.

2.2 Defining the Life Cycle of a Building

One of the most powerful ways to visualize, evaluate and compare the environmental performance of buildings is on the basis of their entire life cycle. The general life cycle concept as it applies to buildings is introduced in this section.

The environmental life cycle of buildings includes all the pre-use, use and end of life impacts incurred by the existence of the building. In more detail, the life cycle of a building includes the extraction of raw materials, manufacturing and processing of construction materials, on site construction activities, operation, maintenance, intermediate transportation between each phase and end of life (which can incorporate reuse, recycling, disposal, or more likely a combination of these). Figure 2.3 summarizes graphically the stages of a building's life cycle. It is important to note that transportation usually occurs between and within each phase. By accounting for all the relevant inputs and outputs through each life cycle stage, it is possible to produce an estimate of the total life cycle impacts of buildings. This will be described in more detail in the following sections. An aspect that is not readily communicated through the figure is that the system is dynamic since technologies are constantly changing. Although the figure shows the life cycle stages as evenly spaced occurrences, the longest stage of a building's life cycle is its operation stage, which typically lasts around 50 years depending on the nature of the building, the local conditions and culture. As shown in the figure, there are several options for the end of life stage, which help a building's life cycle better resemble a closed rather than an open loop.

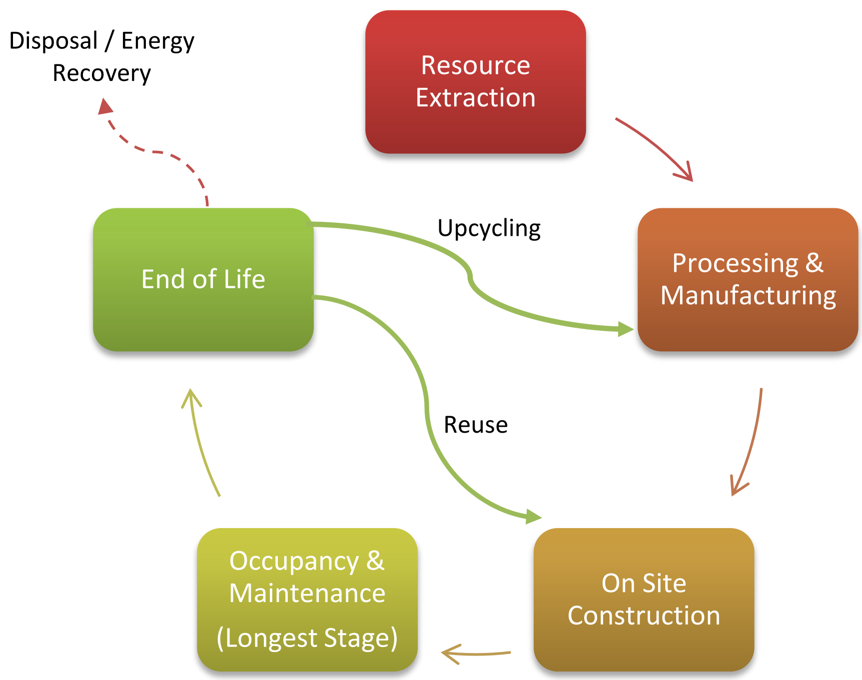

Figure 2.3 Life cycle of a building

The first stage in the environmental life cycle of buildings begins with the extraction of raw materials for all building materials used. This could be the open pit mining for different ores to produce metal or extracting oil from wells to eventually produce plastics. Energy and other inputs and outputs vary depending on the material being produced. Structural engineering decisions that can limit the extent of environmental impact at this stage are related to selecting building materials that require less energy in their production, use less energy intensive modes of transportation, and are produced in a manner that creates minimal waste.

The raw materials are then transported to a facility where they are further processed or manufactured. An example could be drying and cutting boards from a log of Douglas-Fir wood. At the end of the manufacturing stage, it is assumed that materials are in a form that is ready to be installed or used in a building or infrastructure project. In the previous example, this could be a set of 2x4 studs. Structural engineering decisions at this stage relate to the selection of materials that require minimal processing and minimize waste.

The manufactured materials are then transported to distribution centers and eventually to the construction site where construction workers assemble the building as designed. This step is called on-site construction. At the construction site, some waste may be generated from the trimming of certain materials into the sizes required for installation. Heavy machinery such as cranes and backhoes are also likely to be used in site preparation. Regardless of the type of structural assembly, fossil fuels account for the majority of the energy sources used at this stage (Sharrard 2007). Additionally, environmental impacts from the transportation of workers could be significant if construction occurs over long periods of time. Structural engineers can minimize environmental impacts at the on-site construction stage by optimizing structures for quick assembly, assuming all other impacts at other life cycle stages don’t change.

The operation and maintenance stage is by far the longest as it is common to find buildings that exceed 50 years of operation. Due to its length in time, operation usually accrues the majority of environmental impacts, due to recurring energy usage. A way of communicating how energy is used to provide building services can be done through an energy system (Scott 1993). An example of an energy system is presented in Figure 2.4. The diagram outlines the services required by the occupants of a residential building as well as the corresponding energy sources. As shown, an intermediate chain of technologies and currencies is needed to transform the energy source into a service for humans, namely heating, cooling and lighting. It is therefore useful to consider the energy system required to deliver building services since different technologies have different efficiencies.

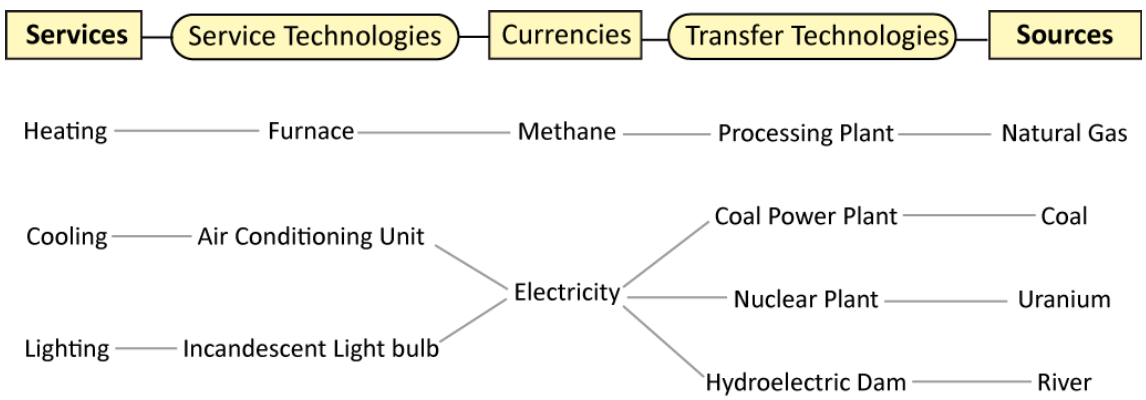

Figure 2.4 Example of a residential building energy system

Regarding the design life of buildings, it has been suggested that in the United States, a considerable portion of the building stock is replaced *before* reaching its design life for reasons ranging from redevelopment to fire damage. A recent North American study of buildings in Minnesota found that over a quarter of the demolished commercial and residential buildings were fewer than 50 years old and that the biggest reason for demolition was area redevelopment and poor physical condition caused by lack of maintenance (Athena Institute 2004). Structural engineers have a shared role with architects and other professionals to minimize environmental impact at this stage. Decisions like selecting the most favourable orientation of the building, optimal window to wall ratio, shading overhangs, thermal breaks for balconies, low energy systems for securing indoor comfort, design for easy repair and flexibility are all important considerations that influence energy use during operation and maintenance.

As indicated by the name of this stage in the life cycle, the operations and maintenance phase has two main components, which occur concurrently in time but are of a different nature. One is the yearly annual energy use associated with the operation of the building, which generally varies depending on the building's location, occupancy and type. It may include a combination of electricity, natural gas or other sources. As one would expect, the energy obtained from the electric grid is daily changing in time and varies depending on the region where it is used.

The second component is the maintenance phase, which is associated with maintaining adequate building assemblies. This includes the recurring replacement of certain components of a building. Certain elements of the building envelope such as paneling, carpet, paint, roof tiles, windows, and other components may have life spans that are shorter than the building's design life. Such building elements may be replaced due to physical wear and tear, but also due to changes in style. Roof shingles could be an example of the former and paint or carpet of the latter. Thus, during a building's life cycle, maintenance is usually of a non-structural nature except in the case of extreme hazard occurrence or poor structural design.

The end of life stage of a building is perhaps the hardest to predict for new buildings, since it happens several decades after construction. Based on current practice, however, it is possible to estimate what the end of life possibilities will be for construction materials in the future. The traditional way in which a building's life ends is when it is demolished or deconstructed and most of the structural and envelope systems are transported to a landfill. There are several possibilities for different portions of the debris generated when a building reaches the end of its life: the waste can be reused in another project, recycled, used as fuel in an energy recovery facility, or transported and deposited to a land fill.

With regards to recycling of building materials, other authors have suggested a distinction between what is called upcycling and downcycling (McDonough and Braungart 2002; Van Nederveen and Gielingh 2009). Upcycling means that with some remanufacturing or reprocessing, a material can be made to match or exceed its original properties and function. For example, a steel beam, when recycled, yields a material that can still be used as structural steel. The other option is for a material to be downcycled, that is, the recycled material is of a lesser quality each time it is recycled and inevitably ends up as waste sometime in the future (McDonough and Braungart 2002). This is the case for office paper or in the construction industry, reinforced concrete. A reinforced concrete beam can be crushed and reused as base material in roads, but it cannot be used again (at least currently) as a structural material. The concept of upcycling also appears in literature under the name of a “closed-loop” material. It has been suggested that the only structural materials that fit this description of a closed-loop material are wood and steel (Sassi 2008). Structural engineers can reduce environmental impacts at this building stage by designing members for easy and convenient disassembly (i.e. through the use of bolts rather than welds in connections) so that structural members may be reused when a building reaches its design life.

As shown, structural engineers and designers can influence each life cycle stage of a building. A summary of the possible design considerations is included in Table 2.1. However, the interventions have consequences throughout the other life cycle stages. It is not uncommon to find materials that have characteristics that are favourable in one stage of a building, but not another. For example, steel may be an energy intensive material during production but it can be upcycled at the end of its life. On the other hand, concrete is extremely durable, but has limited use after its end of life stage. Therefore, answers to environmental questions about what building material is best, are context dependent for a specific project and must consider all life cycle stages. The framework presented in this work helps to answer such questions by recognizing systematically the contributions of all of the stages in a building's life.

Table 2.1 Environmental considerations by building life cycle stage

Life Cycle Stage	Environmental Considerations for Engineers
Extraction & Manufacture	- Use materials that require little energy to extract, transport and process - Use materials that produce minimal waste during extraction and processing
On-site Construction	- Design for fast assembly - Prevent dust and noise - Reduce waste during construction - Encourage low emitting modes of transportation for workers
Operation	- Educate building users on building operation - Optimize of building orientation, heating systems, glazing, envelope, solar shading and other variables by using a building energy model based on local climate.
Maintenance	- Use materials whose durability is a good match for building's design life. - Design for easy repair of components that may suffer damage
End of Life	- Use rapidly renewable materials - Design for adaptability and flexibility of spaces - Use materials that can be easily recovered and reused (limit the amount of paint, adhesives and other finishes) - Maximize use of materials that can upcycled

2.3 Frameworks of Analysis of Buildings

Sustainability assessment tools have the goal of making the long and short term and indirect and direct benefits and impacts of buildings known to all stakeholders. The assessment process is comparable to a medical check-up. If the present state is found to be undesirable, actions may be taken to correct the situation or to prioritize a road to recovery. For this reason, assessments are a key component of the analysis of buildings. They are the tools that help us answer whether a building, a city block, or country is sustainable or not. In the field of structural engineering there are various types of assessment tools that can be generally broken into building rating systems and life cycle based methodologies. In engineering, more generally, there are other tools that, like LCA, are related to the study of material and energy flows.

The different assessment tools presented in this section provide options for determining the environmental impacts of a building. Rating systems are generally comprehensive in scope and qualitative in nature, while LCA is quantitative and fairly specific. In general, LCA will offer a way of relating known information from a building with its environmental impacts throughout its design life. The two general types of assessment tools are presented as well as software tools used to investigate the environmental impact of buildings.

2.3.1 Building Rating Systems

Checklist assessments in the form of rating systems are popular environmental assessments of new buildings. Most rating systems rely on a combination of quantifiable and qualitative measurements but are primarily based on actual or perceived best management practices, often comparing a building design to an established baseline. The most popular North American example of a checklist based sustainability assessment is the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ for new construction or major renovations first launched in 1998 (US Green Building Council).

The number of green building rating systems is growing in many countries. They are administered and overseen by several organizations. Notable examples are the Building Research

Establishment' Environmental Assessment Method in the United Kingdom, arguably the first building assessment tool established in 1990. Others include the Green Star system in Australia, and the Japan Sustainable Building Consortium's Comprehensive Assessment System for Built Environment Efficiency. Three of the entities just mentioned signed in 2009, a memorandum of understanding to collaborate and develop common metrics to measure emissions from homes and buildings (Building Research Establishment 2009). Furthermore, new more rigorous rating systems have been released such as the Living Building Challenge administered by the International Living Building Institute (2010), which requires actual performance data over one year of building operation to demonstrate net zero energy and net zero water usage.

The LEED rating system for new construction contains five main categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality. Each category has prerequisites that must be met for a building to be certified. Additional points can be earned through the additional categories of Innovation and Design Process and Regional Priority. In the end, the points earned for each category are accumulated to determine the final rating of the building. Points are earned by meeting criteria defined in the standard. The different LEED categories represent a shared set among most green building rating systems. Table 2.2 compares the different categories for selected green building rating systems. Common themes are observed through all of them, such as energy, water, materials and indoor air quality. Another shared goal of the different rating systems is that they all advocate what is called an Integrated Design Process which involves approaching the design of a building as a collaborative project of optimizing the whole system and not just individual subsystems. Thus, this requires designers from all disciplines to work together from the early design stage.

Table 2.2 Rating system category comparison (from International Living Building Institute 2010; Building Research Establishment; US Green Building Council; Japan Sustainable Building Consortium 2006)

LEED (USA/Canada)	**LBC (USA/Canada)**	**BREEAM (United Kingdom)**	**CASBEE (Japan)**
• Sustainable Sites • Water Efficiency • Energy & Atmosphere • Materials & Resources • Indoor Environmental Quality	• Site • Energy • Materials • Water • Indoor Quality • Beauty & Inspiration	• Management • Health & Wellbeing • Energy • Transport • Water • Material & Waste • Land use & Ecology • Pollution	• Building Environment Quality & Performance ○ Indoor Environment ○ Quality of Service ○ Outdoor Environment on Site • Reduction of Building Environmental Loadings ○ Energy ○ Resources& Materials ○ Off-site Environment

Figure 2.5 shows the general break-up of how the points are split among each category according to LEED Version 2.2 and its latest Version 3.0. From this figure, it is evident that energy has become an important indicator, which explains why the proportion of points associated with the Energy and Atmosphere category was increased in the latest version. The next category with most points is Sustainable Sites, which has the goal of reducing the on-site impacts of construction, such as not building in ecologically sensitive areas. Most of the credits are evaluated and some are audited to verify adherence to the rating system. A handful of credits, those termed pre-requisites within each category, are mandatory to be considered for LEED certification. In the end, a LEED building is certified to a level according to the number of points it obtains.

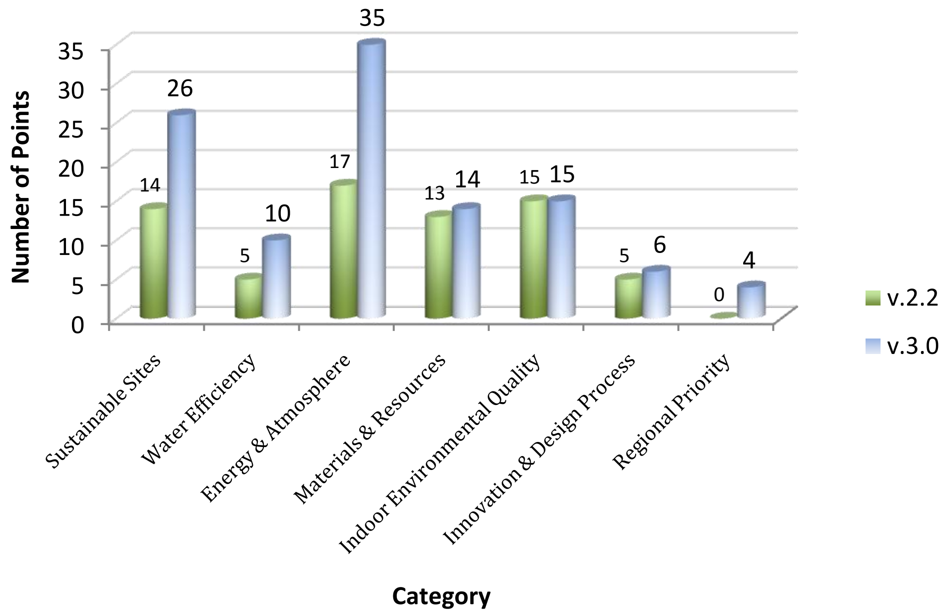

Figure 2.5 USGBC LEED v2.2 and v3.0 for New Construction & Major Renovations points

Building rating systems are favoured by practicing engineers, building owners and other stakeholders because they are relatively easy to implement, they communicate transparently sustainable construction best practices and they provide a competitive business advantage by providing an ecological marketing claim in today's market (Yudelson 2009). The problem with checklist assessments such as LEED is that they are only loosely scientifically based and rely more on consensus about best management practices. The equivalency of the points among the different categories is also debatable. The strength of the rating systems, compared to other quantitative tools, is that they can include a larger variety of criteria and can also easily adapt and change as new knowledge becomes available. This is a key characteristic of LEED, and an understandable one because one of their primary goals is to transform the building market (US Green Building Council 2010).

An interesting development is that many of the rating systems are shaping public policy. California has recently adopted a Green Building Code that incorporates design principles similar to those found in LEED. The International Code Council's (ICC) Sustainable Building Technology Committee is working on the first draft of the International Green Construction Code, which hopes to be adopted by US cities in the future (International Code Council 2010). In addition, the Vancouver City Council has recently approved a policy for requiring rezoning requests to meet LEED Gold (City of Vancouver 2010a). These developments indicate a general shift from the traditional way of building that recognizes the need and importance of reducing damage to the natural environment. In this thesis, the use of rating systems is not viable due to their lack of quantitative impact assessment capability. In fact, in rating systems the decisions on what is environmentally preferable are mostly based on the consensus of a committee rather than a formal scientific procedure.

2.3.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is the tool most widely used in the scientific community to quantify environmental impacts of products (Kibert 2008; Keoleian and Spitzley 2006). Most of the studies published in peer-reviewed journals that analyze the environmental impacts of buildings follow an LCA methodology, although rarely in a consistent manner and not always following its agreed framework as established in the International Organization for Standardization (ISO) standards (Optis and Wild 2010). The framework proposed in this thesis shares with LCA the recognition that decisions, such as selecting materials, have consequences at each life cycle stage of a building. Therefore, all life cycle stages of a building are considered.

Before describing the LCA methodology, it is useful to clarify that LCA is not the same as Life Cycle Costing (LCC). Table 2.3 summarizes some of the important differences between LCA and LCC. Notably, the two types of analyses are fairly different in their scope. Unfortunately, their name is similar, and both are based on life cycle thinking, which often causes confusion. Both tools represent different outcomes: LCC produces economic results (usually one number), while LCA produces environmental impact results (which can be a vector of environmental impact quantities).

Table 2.3 How LCA and LCC differ in purpose and approach (Norris 2001)

Tool/Method	LCA	LCC
Purpose	Compare relative environmental performance of alternative product systems for meeting the same end-use function, from a broad, societal perspective	Determine cost-effectiveness of alternative investments and business decisions, from the perspective of and economic decision maker such as a manufacturing firm or a consumer
Activities which are considered part of the 'Life Cycle'	All processes causally connected to the physical life cycle of the product; including the entire pre-usage supply chain; use and the processes supplying use; end-of-life and the processes supplying end-of-life steps	Activities causing direct costs or benefits to the decision maker during the economic life of the investments, as a result of the investment
Flows considered	Pollutants, resources, and inter-process flows of materials and energy	Cost and benefit monetary flows directly impacting decision maker
Units for tracking flows	Primarily mass and energy, occasionally volume, other physical units	Monetary units (e.g., dollars, euro, etc.)
Time treatment and scope	The timing of processes and their releases or consumption flows is traditionally ignored; impact assessment may address a fixed time window of impacts (e.g., 100-year time horizon for assessing global warming potentials) but future impacts are generally not discounted	Timing is critical. Present valuing (discounting) of costs and benefits. Specific time horizon scope is adopted, and any costs or benefits occurring outside that scope are ignored

LCA involves the comprehensive analysis of selected *potential* environmental impacts and burdens during the "life cycle" of a product. In other words, it represents a full study of the material and energy flows to make a product from extraction of raw materials to manufacturing, use and disposal and the translation of such flows into environmental impacts. Hence, a common phrase used in describing LCA is "cradle to grave", although studies that only look at the pre-use impacts may be termed "cradle to gate" instead (the gate being the manufacturer's exit gate).

LCA accomplishes a comprehensive analysis by using four standard steps as defined in the CSA/ISO 14040 and 14044 standards: 1) goal and scope definition, 2) life cycle inventory analysis, 3) impact assessment and 4) interpretation (Canadian Standards Association 2006a; Canadian Standards Association 2006b). The different steps and their interaction are shown in Figure 2.6. The figure is used to emphasize that the interactions between the different steps are constantly directing which data is gathered and the level of detail of the study.

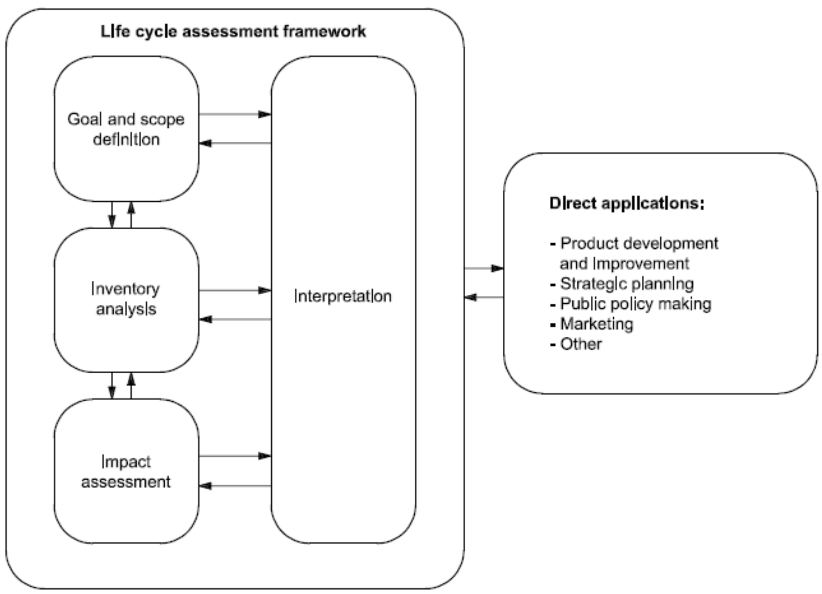

Figure 2.6 Stages in LCA (Canadian Standards Association 2006a)

Originally intended for the analysis of products, LCA presents some challenges when applied to buildings. Some characteristics of buildings that complicate LCA are the complexity of buildings in terms of their numerous material components, evolving technologies in construction techniques and long design life. The use of LCA in the building industry has been identified for its general lack of standardization (Optis and Wild 2010; Blengini and Di Carlo 2010).

Conceptually, an LCA begins with the definition of the scope of the study. The LCA study continues by quantifying all known inputs as well as discharges to air, water and land for every material and process that is of interest. Afterwards, all the material and energy flows associated with each of the material quantities used in the building are aggregated into a long list, called a Life Cycle Inventory (LCI), which is then translated through environmental impact models into actual impact categories such as: acidification, GWP, smog formation, and human toxicity. Finally, the results are interpreted and used to compare different design alternatives or products, improve processes, inform future design or make environmental claims. All of the steps in the LCA process are analyzed in more detail in the following paragraphs.

The first step in performing and LCA is the goal and scope definition. This step outlines the purpose of the study, defines the system boundaries that are considered, states allocation and other requirements. Allocation refers to how processes that produce multiple products are treated within a study. This is important to be able to associate impacts with each product produced. Another key aspect of this step is to define the “functional unit”. The functional unit is what will be used as the basis for comparison and for communicating the results of the study based on the function provided by a product. To illustrate, it may be of interest to see whether a plastic cup is better than a ceramic cup. The functional unit used to compare the performance of the two could be 1,000 uses. Future studies that would like to compare the performance of a paper cup, another product with the same function, could then adopt the same functional unit of 1,000 uses. This allows a better opportunity to compare results from LCAs of different products.

The data collection and all subsequent stages in LCA are strongly influenced by the goal and scope definition step. A general problem in LCA arises when comparing studies, since each one is usually unique in scope. In this thesis, a standard and transparent framework is proposed where the goal is to estimate the environmental impacts of energy usage, water usage and GWP.

The second step is the Life Cycle Inventory, which involves the collection of large amounts of data about the material and energy flows for each stage of the life cycle of a building. There are three main approaches for performing this step: process-based, Economic Input-Output and hybrid. The three alternatives differ in data collection, computational aspects and boundary issues (Suh and Huppes 2005).

For a process based Life Cycle Inventory, data is collected directly or estimated using databases that collect such detailed flow information for various processes. For example, the basic approach is one of establishing a chain of sequential unit processes and combining them to create a whole network that describes the production or life cycle of interest. In the analysis of buildings, unit processes are generally gathered for the production of every material, transportation mode, fuel and end of life option assumed to describe the building's life. The process-based approach is often called a bottom-up approach since it begins with the product and traces the upstream processes required to produce it. This inventory essentially provides an "embodied" environmental intensity value. For example, a Life Cycle Inventory may show that the production of one kilogram of recycled engineering steel requires a total of 13.1 MJ of energy (Hammond and Jones 2008). Thus, if a quantity of steel is known, its production energy can be estimated, assuming a linear model and multiplying the quantity in kilograms of steel with the energy intensity. Additionally, the process-based Life Cycle Inventory document essentially would provide a long list of these flows such as kg of gases, contaminants and waste associated with a reference quantity of product. Therefore, process-based Life Cycle Inventory documents allow the estimation of extraction, manufacture and transport flows for a reference quantity of process. For these reasons, process-based LCA is time consuming and expensive if this data has to be collected, but it also represents more accurate data. In practice, the sequential steps must be truncated at some point, since it is impossible to gather all indirect processes to create a product. This is a part of setting the boundary conditions of the study.

The Economic Input-Output approach is an alternative to the process-based LCA and is often described as a top-down approach. This type of analysis is commonly performed through the use of the Economic Input-Output LCA, a free (for non-commercial purposes) online tool (Green Design Institute at Carnegie Mellon 2010) that models the interdependencies among monetary transactions based on available national economic data. A more recent web-based input-output LCA tool based on similar principles is the Eco-LCA developed at Ohio State University (Center for Resilience). The theory behind these tools was initially established four decades ago through the creation of a linear model of the economic sectors of a country, with an emphasis in simulating their economic interdependencies through the development of Economic Input-Output tables (Leontief 1970). Most governments publish such tables, albeit with different classifications. The Economic Input-Output table for the United States is considered to be one of the most comprehensive (Hendrickson and Lave 2006). Environmental discharges from different sectors can then be used to relate the intermediate and final monetary expenses among industries to produce an estimate of the impacts created by a product. Economic Input-Output LCA is able to capture the entire direct and indirect upstream effects as captured by the linear economic model of the entire economy. Economic Input-Output LCA, however, lacks the degree of resolution that is sometimes required in LCA since the entire economy of the US is represented by 491 sectors. Thus, a user won't be able to distinguish the environmental impact between different strengths of steel, which are likely to have different upstream processes (Green Design Institute at Carnegie Mellon 2010).

Table 2.4 presents a comprehensive comparison of the strengths and weaknesses of each LCA approach as presented by Sharrard (2007). More notably, process LCA is time intensive, as it requires the collection and organization of large amounts of data, most of which is available only by subscription and mainly for European data. Input-output, on the other hand, relies on public information and doesn't require the truncation of a system boundary as the whole economy is included. The fact that it requires fewer data makes Economic Input-Output LCA quicker to use than process LCA. This however, is at the expense of misrepresenting some items, which could be imported, and using a lower resolution due to the industry aggregation. In general, data from process LCA is considered to be less uncertain (Suh and Huppes 2005). Additionally, Economic Input-Output LCA is limited to capturing only the environmental discharges that are required by law to be reported by industries. This may misrepresent the environmental impact of industries that produce relatively small discharges, but who produce and sell larger quantities of products. The Economic Input-Output approach is therefore not used in this thesis because it does not offer the resolution required to realistically describe building components. Perhaps the biggest strength of the Economic Input-Output approach is that it can offer quick reproducible results. Since the focus of this thesis is the analysis of specific buildings, and not of the building sector as a whole, Economic Input-Output analysis is not used.

Table 2.4 Process LCA and Input-Output LCA comparison (from Sharrard 2007)

Topic	Issue	Process LCA	Input-Output LCA
Boundary	Analysis Limits	Subjectively determined based on data availability	Entire U.S. economy (industries, services, etc.)
	Imports and Exports	Can be considered if data is gathered	Must be considered as U.S. products
	Direct and Indirect Impacts	Must be iteratively determined	Automatically included
Data	Type	Public, private, and sometimes proprietary	Public
	Age	Can be extremely recent	5+ years old, at best
	International	Must be obtained	Limited high quality
	Comprehensive?	Can be an issue	Entire economy
	Specificity	Can do specific products	All commodities included, though highly aggregated in some sectors
	Cutting-edge Products	If data is available	No
	Units	Mostly physical	Dollar; difficult to link to physical units
	Uncertainty	Yes	Yes
Life Cycle Phases	Use / Operation	If data gathered	Not included
	End-of-Life	If data gathered	Not included
Results	Type	Can go as far as life cycle impact assessment	Life cycle inventory
	Reproducible?	If data is public	Yes
	Product / Process Comparisons	Possible	Impossible if in same sector
	Process Improvements	Can be targeted	Determinable on sector level only
Investment	Time	High	Low
	Cost	High	Low

The third type of approach includes hybrid methodologies. These have been developed in an effort to combine process data and then supplement information using the Economic Input-Output LCA to capture the upstream effects. There are different ways of combining the use of the process-based and Economic Input-Output approaches. In each case the goal is to combine the strengths of the two approaches and reduce their weaknesses. This approach is not adopted in this thesis but could be evaluated by future work.

In summary, in the application of LCA to the built environment, Life Cycle Inventories of all relevant materials and energy flows are needed to account for the extraction and manufacturing phases as well as production of electricity, transportation and any other processes used during the life cycle of a building. The impacts from subsequent life cycle phases are estimated and summed to provide the total flows of matter and energy in a building's life cycle. Thus, the result of the Life Cycle Inventory step in LCA is a list of inputs and discharges to and from the natural environment caused by the building's construction, which will be utilized in the next step.

The third LCA step is the Life Cycle Impact Assessment. This step is focused on translating all the disturbances and discharges obtained from the previous step into meaningful impacts on the environment. Therefore, while the result of the previous step is a substantial list of inputs and discharges, this step produces a handful of impacts that are organized in categories. There are mandatory and optional provisions according to ISO 14040:2006. The mandatory provisions require the selection of impact categories, their indicators and characterization models. Characterization is done by multiplying the quantities discharged with appropriate characterization factors. For example, an impact category could be global warming potential, which is expressed in units of kg of CO_2e (equivalent) over a time horizon of 100 years and represents the sum of different gases after each is multiplied with characterization factors. A more detailed explanation is provided in section 2.4.3 of this thesis.

Characterization factors are obtained from environmental impact models, such as the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts from the US

Environmental Protection Agency (Norris 2002; Bare et al. 2002). This tool associates inventory data with environmental impact categories which include: ozone depletion, global warming, smog formation, acidification, eutrophication, eco-toxicity, human health criteria pollutants, human health cancer, human health non-cancer, fossil fuel depletion, land use and water use (Bare et al. 2002). The impacts are called "midpoint categories" because they are not necessarily the "endpoint" impacts. For example, for global warming potential, the midpoint impact unit used is kg of CO_2e, whereas the endpoint impacts would include agricultural effects, sea level rise, coastal area damage, species damage and others (Bare et al. 2002).

An equivalent impact formulation has been tailored to the Canadian context under the LUCAS acronym (LCIA method Used for a Canadian-Specific context) proposed by Toffoletto (2007). The impact categories of this LCIA method include: climate change, ozone depletion, acidification, smog formation, aquatic eutrophication, terrestrial eutrophication, ecotoxicity (aquatic and terrestrial), toxicity, land-use and abiotic resource depletion. The need for regional methodologies, stems from the differences in ecosystem sensitivities and climate of different regions, which affect the fate and transport of environmental discharges. It is important to note that the calculation of the global warming potential does not vary among the Canadian and American Life Cycle Impact Assessment methodologies. GWP calculations are standard among nations around the world, unlike other impact categories that are highly sensitive to the *location* of discharges (Norris 2002; Bare et al. 2002; Toffoletto et al. 2007).

Table 2.5 indicates the different impact categories considered in the more commonly used Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts and how they relate to different specific endpoints. This table is useful in describing the breadth of environmental impact categories, their level of specificity and possible endpoints. The more regionally sensitive the impact categories, the less certain they are in LCA since no location information for discharges is generally tracked in current LCA practice.

Table 2.5 Cause-effect chain of impact categories (from Bare et al. 2002)

Impact category	Midpoint level selected	Level of site specificity selected	Possible endpoints
Ozone depletion	Potential to destroy ozone based on chemical's reactivity and lifetime	Global	Skin cancer, cataracts, material damage, immune system suppression, crop damage, other plant and animal effects
Global warming	Potential global warming based on chemical's radiative forcing and lifetime	Global	Malaria, coastal area damage agricultural effects, forest damage, plant and animal effects
Acidification	Potential to cause wet or dry acid deposition	Regional	Plant, animal, and ecosystem effects, damage to buildings
Eutrophication	Potential to cause eutrophication	Regional	Plant, animal and ecosystem effects, odours and recreational effects, human health impacts
Photochemical smog	Potential to cause photochemical smog	Regional	Human mortality, asthma effects, plant effects
Ecotoxicity	Potential of a chemical released into an evaluative environment to cause ecological harm	Regional	Plant, animal, and ecosystem effects
Human health: criteria air pollutants	Exposure to elevated particulate matter less than 2.5μm	Regional	Disability-adjusted life-years (DALYs), toxicological human health effects
Human health: cancer	Potential of a chemical released into an evaluative environment to cause human cancer effects	National	Variety of specific human cancer effects
Human health: noncancer	Potential of a chemical released into an evaluative environment to cause human noncancer effects	National	Variety of specific human toxicological noncancer effects
Fossil fuel	Potential to lead to the reduction of the availability of low cost/energy from fossil fuel supplies	Global	Fossil fuel shortages leading to use of other energy sources, which may lead to other environmental or economic effects
Land use	Proxy indicator expressing potential damage to threatened and endangered species	Regional	Effects on threatened and endangered species (as defined by proxy indicator)
Water use	Not characterized at this time	Regional	Water shortages leading to agricultural, human, plant, and animal effects

Optional elements of the Life Cycle Impact Assessment step are the normalization of the category indicators, grouping and weighting. Normalization involves calculating the impacts relative to some reference information, such as comparing impacts attributable to the process of interest with total impacts produced in a region. Grouping usually involves the ranking of categories in terms of priority. Weighting can also be used to calculate a single scalar environmental impact score using all the impact category results. This is helpful to simplify comparisons, especially to decision makers who may not be familiar with environmental impact categories and their relevance (Keoleian and Spitzley 2006). For example, Blengini (2009), performed an LCA of a residential building using Eco-Indicator 99, a weighting method that produces a single score encompassing various impact categories, such as human health, ecosystem quality and use of resources.

The interpretation phase in LCA summarizes the findings of the study and discusses the associated uncertainties along the entire process such as data quality, availability, assumptions and how these affect the results. Therefore, this step should summarize the limitations of the data used and recognize the relative comparative nature of the LCA study. The results must also discuss how the findings relate to the original goal and scope of the analysis. A final optional component of an LCA is a critical review performed by an expert or a panel of interested parties. This may be required if environmental claims are used for marketing purposes based on the results of the LCA (Canadian Standards Association 2006a).

When using LCA for buildings it is also common practice to keep separate the different elements of the building so that the environmental impact contribution from different elements such as floors, walls, windows or foundations are known. This offers improved insight to inform designers of which assembly groups are responsible for the most environmental impacts.

Overall, the ISO documents for carrying out an LCA study offer very general guidance as to how to perform an analysis and provide a great amount of freedom to researchers, which has prevented standardization necessary to allow comparisons. This is understandable, as the standard is meant to be used for a wide range of products, or which buildings are considered a small subset. In contrast, this thesis attempts to propose a generic methodology that is specifically applicable to buildings, where the inclusion and exclusion of data is made transparently.

2.3.3 Software Tools

Software tools are commonly employed when using LCA for buildings. In North America, the software of choice for carrying out process based LCA studies is Athena Institute's Impact Estimator for buildings (O'Connor and Dangerfield 2004). This is perhaps because it is the only tool specifically targeted to whole building analysis that uses North American data. More refined LCA software is available in Europe, but requires significantly more time in setting up each individual unit process, since it is not set up to handle replacement options and other details that are important when modeling buildings or other long-lived products. In other words, Athena is assembly based while specialized software is material based. Therefore, Athena contains simplifying assumptions that make an analysis quicker, but which may hide some opportunities for minimizing environmental impacts.

Athena's Impact Estimator for buildings software supports the conceptual design stage where design alternatives are explored as a way to understand and reduce environmental impacts. Information describing the building characteristics, such as bays, spans, materials, location, expected loadings, building type and expected life, is entered into the program and processed by the software to produce a bill of materials listing aggregated areas, volumes and quantities of materials such as gypsum board, lumber, wide flange steel, rebar, polyethylene, or any other material used in the building structure or envelope. Athena has developed Life Cycle Inventories that are then used in conjunction with building type replacement rules to capture recurring life cycle impacts (Athena Institute 2010a).

Annual energy use during operation is a piece of information that must be supplied to the program. Such information is generally obtained from more detailed energy modeling software or from expected energy use based on experience with similar buildings. These yearly fuel and electricity requirements are input to the software and presumably translated to discharges and impacts using regional data on electricity source mix. In the end, all the discharges associated with each material type are multiplied with characterization factors to produce estimates that include primary energy consumption (MJ), acidification potential (moles of H+ equivalent), GWP (kg of CO_2 equivalent), human health respiratory effects potential (kg PM2.5 equivalent), ozone depletion potential (kg of CFC-11 equivalent), smog potential (kg of NO_x equivalent), eutrophication potential (kg of N equivalent), and weighted resource use (kg). The software also allows the disaggregation of results in terms of type of assembly elements and in life cycle stages.

A free scaled down version has also been developed in the form of spreadsheets provided by Athena through a project called EcoCalculator (Athena Institute 2010b). This spreadsheet tool does a similar life cycle estimate using average data from previous Impact Estimator building studies and additional assumptions and includes all building life cycle stages except operation. The inputs are similarly based on quantities of materials, although not all the impact categories normally available in the Impact Estimator are included in the results. This application was developed to be used within a rating system called Green Globes, which is slowly gaining ground in North America as an alternative environmental building assessment to LEED (Green Globes 2010). Thus, the EcoCalculator spreadsheet offers a quick LCA-based analysis alternative for designers.

There are other design tools used to estimate energy use. One example is Green Building Studio (Autodesk 2010), which is a web-based service that imports 3-D Building Information Models and produces estimates of annual energy usage, water consumption and energy cost during operation. Users are required to first create a model of the building including windows, wall, internal partitions and thermal zones. The service uses the building location information, size and building type to produce its estimates. A user can then explore different technologies such as glazing type for different wall orientations and daylight sensors in an iterative fashion to optimize energy usage and cost. Finally, the service allows the export of input files to more refined energy building simulation software such as EE4, eQuest or EnergyPlus (U.S. Department of Energy 2010).

Finally, other specialized LCA software is available (National Institute of Standards and Technology 8/20/2007; PE International 2010). However, as discussed earlier, the lack of comprehensive and high quality databases for North American data and absence of tools tailored to buildings is problematic. This software also has a very high cost due to the need to subscribe to a high quality database, which is expensive to maintain.

The present work is similar to the implementation offered by the software previously mentioned. However, explicit information regarding material quantities and intensity values is required from the user. The operation phase is also first calculated externally through the use of energy modeling software. However, explicit models for the operation phase are included for estimating energy and water using coarse resolution data. Thus, a higher degree of flexibility and transparency is offered.

2.4 Environmental Impact Indicators

This section provides background on the environmental impact indicators that are suggested for quantification in this thesis. The following provides a complete definition of what indicators are:

> Indicators can be defined as statistics, measures or parameters that can be used to track changes of environmental or socio-economic conditions. Indicators are developed in synthesizing and transforming scientific and technical data into fruitful information … It can be used to assess, monitor and forecast parameters of concerns towards achieving environmentally sound development (United Nations Environment Programme and Regional Resource Centre for Asia and the Pacific 2004).

Indicators are a pivotal part of the sustainability assessment process. The word “metric” could be used interchangeably with the word indicator. The term indicator will be used here to describe the direct or indirect measurement of parameters that are believed to influence environmental sustainability of buildings. In the previous discussion of LCA, some environmental impacts have been briefly covered. This section describes the indicators that are employed in this thesis.

2.4.1 Energy

Energy usage is meant to measure the demand for energy input. Energy is neither created nor destroyed, so the term usage in the context of buildings refers to the required energy demand to provide necessary building services (including the unintended irrecoverable losses to the environment). Energy usage is important since it has been considered a reasonable proxy for the intensity of resource use and overall environmental impact (Cuddihy et al. 2005; Keoleian and Spitzley 2006). Furthermore, the distinction between primary energy and end-use energy has been recently emphasized by researchers (Gustavsson et al. 2010; Ramesh et al. 2010). Primary energy is analogous to the idea of energy return on investment, and it is used to recognize the energy used to extract, transport, and process fuels before they are used (i.e. by including transmission losses, conversion efficiencies). Thus, it is reasonable to state that lower the primary energy usage (at least with the current heavy reliance on fossil fuel combustion) the lower environmental impacts caused by the life cycle stages of buildings and infrastructure. The unit that is used to quantify primary energy usage in this study is Joules (J).

2.4.2 Water Usage

Water usage is an important indicator of environmental impact because it requires the construction and maintenance of facilities for water treatment, pipe networks to deliver water to a building, and the removal of wastewater (Filion 2008). Even in high buildings, energy may be required to maintain sufficient water pressure (Cheng 2002). Furthermore, at a regional urban level, water scarcity is a growing concern, primarily due to the accelerated growth of cities. Replacing the pipes used for the conveyance of water is part of the ballooning costs of aging infrastructure faced by cities. This has implications on the resilience of a community, as water is a basic service essential to human life. This is particularly true in the aftermath of hazardous events, when the distribution systems suffer interruptions due to damage of water mains or loss of pumping capacity due to loss of electricity. It should be noted that water issues are generally divided into the two categories: quantity and quality. Thus, the indicator chosen in this thesis only addresses the issue of quantity in the form of water demand, and ignores the quality, or degree and extent of contamination, resulting from its use. These are important considerations that should be addressed in the future. Water usage is measured in litres of water.

2.4.3 Global Warming Potential

Global warming potential (GWP) is an environmental impact indicator used as a measure of the warming effect caused by anthropogenic, or human-caused, emissions. The increase of these "greenhouse" gases in the atmosphere leads to a net warming effect that may have adverse effects, such as sea level rise and changing weather patterns (Bare et al. 2002). The primary reason for the greenhouse effect is that the rate of production of these gases due to human activity exceeds the rate of absorption provided by oceans and vegetation (MacKay 2009). GWP has units of kg of CO_2e (equivalent) and is normally calculated over a 100 year time horizon. Note that the choice of time horizon affects the calculation of non-CO_2 gases only, as CO_2 is itself the reference gas used, independently of the time horizon chosen. Table 2.6 presents some of the gases, their atmospheric lifetimes and characterization factors which are used as weights for each respective gas in calculating GWP for a 100 year time horizon. The need for a time horizon is necessary because the gases are constantly reacting and changing in the atmosphere, and therefore their warming effect is changing in time.

Table 2.6 Greenhouse gases, atmospheric lifetimes and weights for a 100-year time horizon

Gas	Atmospheric Lifetime In Years	$GWP_{100\ years}$
CO_2	50–200	1
CH_4	12 ± 3	21
N_2O	120	310
HFC-23	264	11,700
CF_4	50,000	6,500
C_2F_6	10,000	9,200

Gas	Atmospheric Lifetime In Years	$GWP_{100\ years}$
C_2F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

The weights are applied to the total quantities of greenhouse gases, which allow their combination into the common metric of kg of CO_2e. The choice of time horizon has been recommended by the Intergovernmental Panel for Climate Change (IPCC 2010) and its use has been primarily for national greenhouse gas accounts. It has recently been suggested that a 100 year time horizon may be misleading for long-lived products such as buildings because the different emissions occur at different times, yet they are usually treated equally (Levasseur et al. 2010). For the present study, however, the 100-year time horizon is adopted for the calculation of GWP.

Among the environmental impacts traditionally included in LCA, GWP is most relevant on a global scale and its application is generally standard. Due to its perceived lower level of uncertainty, which is evidenced by the uniform consensus on its calculation, it is included in this study. In contrast, other environmental impact categories, such as eutrophication and smog formation, are believed to be highly uncertain, particularly when the location of environmental discharges is not known.

The importance of quantifying GWP is that it is recognized as an environmental impact of global relevance. Additionally, it is strongly related to the manufacture of building materials. Production of Portland cement, for example, produces CO_2 emission that arise both from its chemical reaction and the energy required to reach the temperature for pyroprocessing. With the increasing use of on-site renewable energy sources for buildings, it is also believed important to quantify the benefits that such design choices provide. If only energy was tracked, the benefits from the use of such technologies would not be evident. Therefore, GWP is a relevant impact in the study of buildings.

3 Previous Environmental Impact Studies

This chapter provides an overview of earlier studies on the environmental impact of buildings. The methodologies, insights and findings are contrasted with the work presented in this thesis.

LCA represents the most rigorous scientific environmental study for products (Kibert 2008; Keoleian and Spitzley 2006). Consequently, most of the published academic research is focused on this type of assessment. The three varieties of LCA studies: process, input-output and hybrid are all found in the literature, although variations within the methodologies are common.

3.1 Life Cycle Studies of Buildings

A variety of approaches are found in the literature. Early assessments attempt to quantify energy, while more recent studies make use of software tools to develop estimates of impacts ranging from global warming potential, to eutrophication and smog formation. The goal of this review is to provide insight into the calculation of different environmental impacts. However, the majority of studies reported in the literature rely on software that is used as a "black box" with little or no discussion of its inner workings and assumptions. The most informative studies are cited in the following.

Cole and Kernan (1996) presented a study that predicted the life cycle energy use of a generic office building constructed from wood, steel and concrete structural systems with and without underground parking. The study included the energy used to produce the building, refurbish and maintain the building, operate the building by conditioning the space, and energy used to dispose and demolish the building. The embodied energy is presumably estimated by quantifying the different materials used in the building and multiplying each material with an embodied energy intensity value (i.e. GJ/kg). However, no comprehensive list of values used is provided. Energy usage during the operations phase represented the biggest percentage with respect to the entire life cycle of the building. This stage was calculated using a building energy simulation program DOE-2.1D. An important finding of the study is that energy used for maintenance due to changes in building fit-out (such as doors, floor and wall furnishings) can accumulate significantly in the case of buildings with longer lives. The demolition phase was estimated with values from other studies. Cole and Kernan argue that focus should be placed on improving energy efficiency because the initial embodied energy represents less than 5% of the total energy used during the life cycle of 50 years. The authors emphasize that when the energy use during operation is reduced by roughly 30% compared to the provided example, the initial embodied energy as a proportion of total life cycle energy use would become dominant.

Adalberth (1997a; 1997b) presented a comprehensive life cycle study on residential building energy use. By using estimates of energy intensity of building materials and additional information, such as waste material during construction, assembly replacement frequency, yearly energy usage and demolition, the author estimates life cycle energy requirements of three prefabricated wood structure residential buildings in Sweden. The author provides a list of such energy intensity values as well as approximated percentages of waste mass for each construction material. Waste percentage values are used to reflect the need for additional materials during construction due to trimmings and other waste. The basic life cycle quantification procedure outlined by the author greatly resembles the framework proposed in this thesis although with the difference that Adalberth's is deterministic in nature and only analyzes energy. In that study, energy intensity values are used to relate energy to material mass quantities and replacement frequencies are considered. In other words, energy intensity values of the form kWh/kg are multiplied with each construction material mass in the project to determine total embodied energy. The procedure is extended to the other life cycle stages. Energy use during operation is estimated using a building energy simulator to produce an annual estimate that is multiplied by the selected time horizon of 50 years. The author reports some of the relative proportions of materials used in the residential construction case study. Concrete, as expected, is a big contributor to the manufacturing energy use by weight, and plastic, although not heavy (1-2% of total weight), is found to contribute 18-23% of the total life cycle energy use. Interestingly, transportation and process energy is determined to be about 1% of the total life cycle. The author concludes with three recommendations: to reduce energy demand throughout the operation phase of a building, monitor construction to ensure quality workmanship, and use materials with reduced amounts of embodied energy.

Jonsson et al. (1998) presents a comprehensive LCA of seven concrete and steel frames representative of construction in Sweden. Although little discussion is provided on the calculation aspects of the study, the authors point out that in the analysis of buildings the complexity is greatly increased due to the number of materials involved. This can lead to calculation errors and complicates transparency. The authors call for the advancement of software tools that help overcome these difficulties and help detect “hot spots” in the chain. This thesis addresses this challenge.

Cole (1998) presents an analysis of energy and greenhouse gas emissions in Canada during construction for three different structural systems: steel, wood and concrete. Cole used data from surveys of construction professionals and worker hour estimates from an R.S. Means publication (Cleveland 1988) to develop estimates of construction activities and translate them to energy requirements and emissions. By focusing on the relative performance of the structural systems, it is established that there is a difference in energy and greenhouse emissions during the construction phase, with concrete assemblies generally producing an order of magnitude greater emissions than wood or steel. An innovative approach is that worker transportation is included and found to significantly increase energy and emission estimates. In this thesis, a similar approach is taken to estimating the environmental impacts during the construction phase. However, the amount of worker hours is used as an indicator of environmental impact instead of individual construction activities.

Junnila and Horvath (2003) carried out a comprehensive LCA of an office building in Finland. One of the innovations in their study is the expansion of impact categories to include climate change (tons of CO_2 equivalent), acidification (kg of SO_2 equivalent), summer smog (kg of H_2C_4 equivalent), eutrophication (kg PO_4 equivalent) and heavy metals (kg Pb equivalent) in addition to energy use. The study found that different categories are significant at different stages of the building's life cycle. The emission data associated with building materials was obtained directly from the manufacturers and verified by an independent third party. The authors list the top ten elements accounting for the majority of the environmental impacts: "…electricity use in lighting, heating ventilation and air conditioning, and outlets; heat conduction through the structure; manufacturing and maintenance of steel, concrete, and paints; water use and wastewater generation; and office waste management." In addition, it is stated that operational energy accounts for 65-75% of climate change and acidification impacts of buildings. Few technical details are offered on how the life cycle estimate was developed for each environmental impact category, although the results obtained are discussed at length.

Scheurer et al. (2003) analyzed a university building in Michigan with an expected life span of 75 years using LCA and focused on a wide range of impact categories including: GWP, ozone depletion potential, acidification potential, eutrophication potential and solid waste generation. Material intensity data was obtained from various public and subscription databases and SimaPro software. Construction phase intensity was obtained using modified values from the previous study by Cole (1998) on construction energy. Replacement frequencies of materials are assumed and reported. The operational stage energy use is calculated using a computer energy modeling software program called eQuest. The decommissioning phase of the building is estimated using a published study from the Athena Sustainable Materials Institute. It is found that all the considered impact categories correlate well with energy intensity. The primary energy usage intensity is found to be 316 GJ/m^2 and the building demolition stage is found to be only 0.2% of the life cycle primary energy consumption. As in previous studies, it is found that operational energy accounts for a significant percentage of the environmental impacts that were incurred. The issue of sensitivity of the results to replacement rates is emphasized. A feature that sets this study apart from others is that the authors track the water usage resulting in a life cycle total of 3.6×10^6 litres per year for the considered structure. An alternate way of communicating life cycle totals proposed in this thesis is on a per occupant basis over the life cycle of a building. It is argued that this form is more informative since similar buildings may have similar functions and size, but serve different numbers of people.

A hybrid LCA approach was performed by Guggemos and Horvath (2005). The authors investigated the LCA performance of two 4,400 m^2, five-storey, office buildings, one made with a structural system of steel and another of reinforced concrete. The authors defend the selection of the two structural types by stating that they are the two primary building types used for commercial buildings. The authors use the Economic Input-Output LCA (Green Design Institute at Carnegie Mellon 2010) for some stages and process data and models for the remaining phases in the life cycle. One interesting simplification is that the authors used published energy code averages for the annual electricity and natural gas consumption associated with the building instead of using a computer energy model for each particular structure. The authors found that considering the uncertainties in the data, no preference was reached for an environmentally friendlier alternative. Both structures were found to use roughly the same energy over the life cycle. The use phase was still dominant, but the authors note that once energy efficient design becomes widespread the other life cycle stages will become more important.

Dong et al. (2005) studied the implications of retrofitting a house instead of building a new one using LCA alongside of LCC. For this purpose three residences in Toronto are considered, two wood framed and one masonry and built at different levels of required insulation. The analysis involves possible energy retrofits to each house or the alternative rebuilding option, where the new house meets stringent current energy standards. The authors recognize that achieving better energy performance is more complicated for retrofit projects. The retrofit decisions are narrowed to those that are most feasible, economical, and perceived to make the biggest difference in building energy performance. The authors use Athena's Impact Estimator, construction cost data, and a 3D house model to estimate required quantities for each of the options. The results indicate that, although the rebuild option results in lower greenhouse gas emissions and lower energy use, the retrofit options produce less waste and water contamination. Furthermore, the retrofit option has a lower life cycle cost.

Thormark (2006) emphasized the importance of looking at embodied and end of life environmental impacts of buildings. The author reports mixed results from previous studies, some claiming energy savings as high as 40% when using recycled rather than virgin materials. The author claims that such differences are caused by conflicting assumptions regarding recycling rates as well as material composition of buildings studied. In all cases, however, energy savings are deemed feasible through the use of recycled materials. The focus of the study is the embodied energy and recycling potential of a multi-family housing complex of 20 apartments in Sweden. The authors define the recycling potential as the embodied energy of the material being substituted times a fraction used to represent the remaining lifetime, minus the energy used to transport, upgrade the material for reuse or recycling. Insufficient guidance is offered on how these values are calculated. Using this recycling potential as an indicator of environmental impact, the base building is studied for two scenarios, one for a minimum case of recycling and energy recovery and another for maximum reuse. Little change is found between the two, with maximum reuse being marginally better. The importance of recognizing the end of life phase, the use of low embodied energy materials with little maintenance, and design for easy disassembly are stressed as favourable design alternatives from an environmental impact point of view.

Zabalza Bribián et al. (2009) present a methodology for the simplified life cycle assessment of buildings. The authors suggest the use of two main indicators: primary energy in kWh and carbon dioxide measured in kg of CO_2e. The methodology estimates the embodied energy and carbon of building materials and the operational energy throughout the operation of the building and is then applied to an example residence in Spain. It is suggested that the embodied energy and carbon due to the construction materials is significant and should become a part of the energy certification process of buildings, since analyzing only the operational phase does not necessarily lead to optimal buildings from an energy and carbon perspective. In this thesis the quantification of energy and global warming is endorsed with the addition of water usage. Unlike the proponents of this simplified methodology, an effort is made to quantify all of the life cycle phases of a building.

Blengini and Di Carlo (2010) present an LCA study of a low energy Italian house to analyze how its energy usage during operation relates to its entire life cycle performance. The authors note that recent studies of low energy buildings suggest that embodied energy can dominate the percentage of energy incurred over the life cycle of a building. The results suggest that the environmental performance of the house is not as superior as thought by only comparing operational performance. The ratio of the *operational* energy usage of the traditional design to the low energy house is 10:1, while the ratio is merely 2.1:1 when the entire life cycle is considered. Transportation was found to have a minor contribution to GWP: around 2%. This study is valuable since it presented one of the most detailed end-of-life analyses, which includes reasonable values for recycling and dismantling. The findings demonstrate that consideration of the end-of-life phase is important in minimizing environmental impact. Thus, buildings that are designed to use very little energy during the operational phase should be studied from an LCA perspective to assure an optimal balance between performance during operation and pre-use and end of life impacts. This view is endorsed in the present work by considering all of the life cycle stages of a building.

There are several general issues worth noting regarding previous life cycle studies of buildings. First, most studies fail to expose in sufficient detail many of their procedural steps in estimating environmental impacts and many fail to follow basic ISO guidelines, possibly due to journal article length restrictions (Optis and Wild 2010). The majority of studies rely on the use of software tools that are not fully transparent with regards to their assumptions or they rely on subscription-based inventory databases.

The literature on sustainability and buildings is also fragmented among different building types, i.e. residential, office, and university buildings. This suggests a difference in procedures for performing LCA type analyses based on primary building function. When analyzed more closely, however, the primary difference in application methodology occurs in the building operation and maintenance phase. By contrast, this thesis puts forward a methodology that is universally applicable to multiple types of buildings serving different functions.

A common finding of recent environmental impact studies based on LCA is that for low energy buildings, net zero energy buildings, and others that aim to produce as much energy as is consumes during a year in operation, the accurate quantification of their non-operation related impact is paramount, and no life cycle stage can be justifiably ignored (Blengini and Di Carlo 2010; Hernandez and Kenny 2010; Brunklaus et al. 2010). This further motivates the methodology proposed in this thesis, which attempts to capture all life cycle stages.

It is notable that the end-of-life aspects of buildings have been generally ignored or minimized, although some notable exceptions exist (Blengini and Di Carlo 2010; Canadian Standards Association 2006c; Gorgolewski 2006). Perhaps as the end-of-life considerations are studied in more detail there will be increased interest from designers, including structural engineers, who will favor methods of construction that more easily permit disassembly, reassembly and design for flexible and adaptable use of buildings. Such analysis must adopt a long time horizon that captures the dynamic changes of cities and their building stock.

Research is scarce on developing countries, which are expected to play a major role in the energy security of the future (Pérez-Lombard et al. 2008). The major obstacle in this domain is the absence of relevant data on construction techniques and impact intensity values. Nonetheless, the presented framework remains relevant and useful in the context of developing countries.

Many of the proposed strategies for reducing energy use are technology-based (Ramesh et al. 2010). This follows from the technology-oriented nature of building energy models. Occupant knowledge and behaviour is now gaining interest as a tool for understanding energy use during building operation (Brown and Cole 2009). Uncertainty analysis in building energy simulation models is also gaining interest (Domínguez-Muñoz et al. 2010). These are important developments since the operation phase of a building is very long in comparison to other stages.

The lack of standardization in LCA practice for buildings presents an additional challenge, which at the moment prevents the adequate comparison of research results since it is not always evident what assumptions different researchers have made in their studies. Additionally, software implementations of LCA are very expensive due to the required level of data collection and updating of Life Cycle Inventory data. LCA software that is tailored to building assemblies, like Athena, on the other hand, contain a fair amount of simplifying assumptions that reduce the opportunities to minimize environmental impacts. Other tools, like Economic Input-Output LCA, although free for non-commercial use, are often used as “black boxes” (similarly to other LCA approaches) where the underlying interrelationships and associated uncertainties are much harder to understand. Thus, the methodology that is proposed in this thesis highlights transparency in the estimation of the intensity factors, and properly accounts for their uncertainty. While LCA offers numerical results, there is currently limited discussion on the range of uncertainties present within each environmental impact category.

3.2 Uncertainty in Life Cycle Assessment

LCA, as shown in the previous section, represents the most popular approach to estimate the environmental impact assessment of buildings. However, uncertainty has been identified as a limitation to the widespread and meaningful use of LCA (Huijbregts 1998; Ross et al. 2002). An argument that has been voiced by proponents of LCA is that the uncertainties that are present when performing comparisons are positively correlated, and therefore, the information obtained from LCA is still useful for carrying out relative comparisons (Hendrickson and Lave 2006). This is because the variability from different processes may have shared characteristics, and therefore, the uncertainty of their *difference* is smaller than that from analyzing each process alone (Hendrickson and Lave 2006).

Huijbregts (1998) examined the different types of uncertainties that exist in LCA in an effort to understand what approaches may best address each of them. The author states that the main motivation for such study is the realization that uncertainty is commonly identified as a weakness in LCA. The author distinguishes between uncertainty and variability, the former being due to model assumptions, insufficient data, or inaccurate measurements, is reducible, while the latter is considered an inherent characteristic of the real world. In this thesis, we prefer to use the structural reliability categorization of uncertainty as aleatory or epistemic; in Huijbregts' paper the equivalent terms are variability and uncertainty, respectively. The author lists six specific types of uncertainty and variability: parameter uncertainty, model uncertainty, uncertainty due to choices, spatial variability, temporal variability and variability between objects and sources. Regarding parameter uncertainty, Huijbregts suggests that the Life Cycle Inventory flows should be collected including ranges developed from expert judgment. Similarly, processes with little or no data should be studied further. The ultimate goal in LCA, in the view of Huijbregts, would be the characterization of the distributions of the data gathered as well as their correlation. Model uncertainty is another source of uncertainty in LCA. This type of uncertainty is associated with the environmental impact phase of LCA, where, since space and time are not tracked, impact models are greatly simplified. Uncertainty due to choices is a result of the decisions a researcher performing an LCA faces, such as choosing a functional unit, allocating impacts from multi-output processes or the optional LCA practice of applying weights. For this, Huijbregts recommends investigating different scenarios and seeing how they affect the estimates. The temporal and spatial variability stems from the lack of tracking in LCA, but they present challenges that are hard to overcome. The difference between objects and sources is a final source of error in LCA since technologies are often different for similar processes. Huijbregts concludes by discussing the difficulty of estimating uncertainty ranges for all parameters in an LCA study. Being transparent is heavily endorsed. The author also proposes to investigate, in future research, the implications that the explicit treatment of uncertainty holds for decision makers.

Ross et al. (2002) compares how the ISO standards propose to deal with uncertainty and how studies from practitioners deal with uncertainty. Generally, the ISO documents contain warnings about performing quantitative uncertainty analysis and avoiding aggregated life cycle inventory data since it is harder to match specific systems with aggregated ones. Thus, the authors hypothesize that if the recommendations from the guiding standards are followed, then published studies must have mentioned or recommended better assessment for certain impact categories. The authors investigate 30 LCA studies and attempt to track which ones take a quantitative or qualitative approach to the uncertainty and what the uncertainty concerns relate to. It is found that only two out of the thirty LCA studies perform a qualitative analysis of the uncertainty of the impact assessment, even though more than half of the total studies claim to comply with the ISO methodology. Furthermore, it is found that very few studies questioned how accurate the impact assessment methods are, the impact of the aggregation of data over temporal and spatial scales and more generally, the role that the limitations of the inventory step has in uncertainty in LCA. The authors suggest that this lack of understanding of uncertainty and its effect on the results is a threat to the credibility and relevance of the use of LCA and could result in misguided developments and poor policy directions.

In summary, uncertainty is a topic that is loosely covered in LCA studies and often limited to sensitivity analysis. A major obstacle in this respect is the lack of information on the statistical distributions of material and energy flows as captured in Life Cycle Inventories and the perception that the implementation of uncertainty computational analysis that includes such statistical information is computationally intensive. Thus, most studies addressing the environmental impact of buildings have been limited to some level of sensitivity analysis and Monte Carlo analyses. The lack of uncertainty analysis may be due to the lack of convenient tools to accommodate their analysis. The probabilistic models presented in the next chapter directly address the need to include uncertainty in environmental impact calculations. Importantly, they are also intended to provide motivation and direction for future improvement of environmental impact prediction models. At this time, due to lack of statistical information, engineering judgment plays a significant role.

4 Environmental Impact Models

> *During the three years which I spent at Cambridge my time was wasted, as far as the academical studies were concerned, as completely as at Edinburgh and at school. I attempted mathematics, and even went during the summer of 1828 with a private tutor (a very dull man) to Barmouth, but I got on very slowly. The work was repugnant to me, chiefly from my not being able to see any meaning in the early steps in algebra. This impatience was very foolish, and in after years I have deeply regretted that I did not proceed far enough at least to understand something of the great leading principles of mathematics, for men thus endowed seem to have an extra sense.*
>
> Charles Darwin's 'Autobiography' (1958)

4.1 Analysis Framework

The design of civil infrastructure entails a number of decisions with economical, environmental, and social impacts. The decisions relevant to building designers may include selecting the building location, shape, window-to-wall area ratio, orientation, load-carrying system, self-shading, material selection, and member dimensions. Each decision affects the functionality, safety, energy usage, operation costs and other social, economic and environmental performance criteria of a building. The fundamental vision behind this thesis is to provide a framework to help decision makers make the optimal decisions, using models that predict environmental impacts.

As pointed out in the literature review, decision support tools that consider the balance between cost and safety have already been contemplated although neglecting environmental considerations (Sanchez-Silva and Rosowsky 2008; Sanchez-Silva and Rackwitz 2004). This thesis addresses this shortcoming, but not in the same framework as established by Sanchez-Silva and Rackwitz (2004). Instead of formulating the costs and benefits algebraically in a scalar, additive objective function, the approach adopted in this thesis makes use of classical structural reliability algorithms in conjunction with probabilistic models. This type of analysis and the strategy for developing the required models to predict environmental impacts is explained in the following.

As an introductory example, consider the need for deciding which material to use in the load-bearing structure. Structurally, the alternatives may include steel, timber, and reinforced concrete materials. Typically, such decisions are made based on cost, aesthetics, function, desired performance and perhaps subjective judgment and previous experience. Clearly, a transparent decision tool that includes environmental impacts in a comprehensive "cost-benefit" consideration would be useful. In this example, certain materials may become less appealing if their respective environmental impacts are included and assigned ample weight. This idea is easy to promote, but entails several challenges. First, it requires the direct and indirect impacts (economical, environmental, and social) to be quantified and collected in a single utility function, for example dollar value. Multi-objective decision-making, where multiple variables are optimized at one time, using Pareto sets or similar techniques, is not subscribed to in this thesis. Second, the dependence of the impacts on discrete or continuous decision variables must be identified so that the utility function can be maximized with respect to those variables to identify the best decision. In the context of the example in this paragraph, the economical, environmental, and social impacts of selecting steel, timber, and reinforced concrete must be computed, aggregated in a shared utility value, and compared.

If impacts could be predicted with certainty then the best decision could be identified as soon as the various impacts were quantified. However, engineering inherently entails making decisions under uncertainty. Classical structural engineering recognized early that the loads on a structure, and even the strengths of materials, are uncertain. Hence, the prediction of both is made through the use of probabilities. The presence of uncertainty adds a layer of complexity to the aforementioned vision for a decision support tool. Specifically, the economical, environmental, and social impacts are functions of random variables as well as decision variables.

To understand the analysis that will identify the best decision, assume that impact models are established that produce, say, dollar amounts that depend on decision variables and random variables. The field of reliability-based optimization (Haukaas 2008; Polak 1971; Liang et al. 2007) addresses this type of problem. Several analysis strategies are available. One can identify the value of the decision variables that maximizes the mean benefits (or, equivalently, minimizes the mean cost). One can also carry out the optimization at some other probability threshold (Haukaas 2008), such as the maximum tolerable exceedance of energy use. Although the details of such analyses are outside the scope of this thesis, the key characteristic of this analysis framework is emphasized: it requires models that predict some measure(s) of impact, e.g., dollar values, as function of continuous or discrete decision variables and random variables. In the following these are referred to as probabilistic models.

4.1.1 Probabilistic Models

An example of a probabilistic model is the structural analysis model of a building. This model contains structural elements that are defined in terms of geometry and material parameters. Furthermore, it takes parameters that define the loading. Consequently, the user of this model can characterize the material and loading parameters (whose variability is outside the control of the designer) as random variables and the geometry parameters as decision variables (which are values that the designer may influence). Another example of what a probabilistic model is in the context of this thesis is an algebraic equation that receives the amount of reinforced concrete and steel as inputs and computes the amount of embodied energy due to extraction and manufacturing. More formally, the definition of a probabilistic model adopted in this thesis is:

- A predictive model that explicitly accounts for uncertainty by receiving random variables as inputs;
- An input-output model not restricted to single scalars;
- Produces deterministic output for specific realizations of the random variables;
- Yields output covering the entire outcome space; and
- Accounts for both epistemic and aleatory uncertainty. Epistemic uncertainty is the uncertainty associated with each model, which can be reduced over time by improving the model, while aleatory uncertainty is the irreducible inherent uncertainty the physical process (Haukaas and Bohl 2009).

Figure 4.1 describes visually how a probabilistic model receives random variables as inputs and produces output. Figure 4.2 shows how the environmental impact models fit within the larger Unified Reliability framework implemented in Rt, where it receives output from upstream models, reads data from a building information model and provides output that can in turn be fed to other models that goes back to the reliability analysis module.

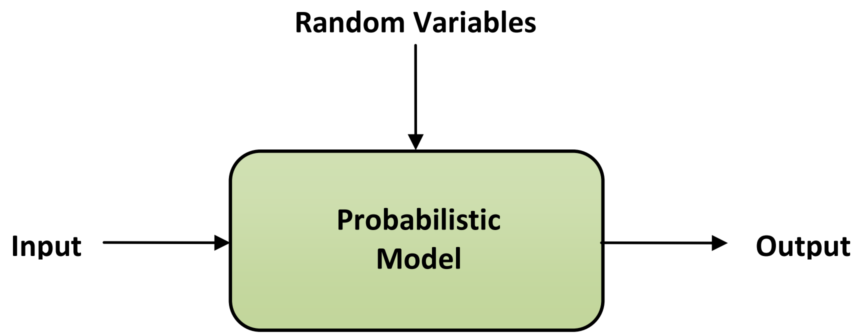

Figure 4.1 Conceptual probabilistic model description

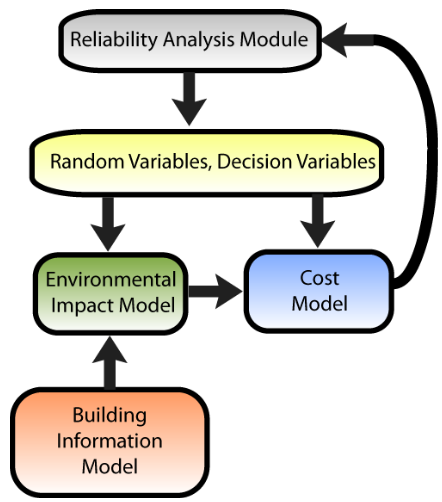

Figure 4.2 Probabilistic environmental impact model and its place within overall framework

Within the definition that is enumerated above, a probabilistic model may have many forms. It may be an algebraic equation, a computer algorithm, the solution to a differential equation, a neural network formulation, etc. In the following it will be assumed that the probabilistic model is an algebraic equation of the form,

$$y = \theta_1 x_1 + \theta_2 x_2 + \ldots + \theta_n x_n + \varepsilon \quad \textbf{(4.1)}$$

where y is the impact to be predicted, such as life cycle energy usage, x_i are physical measurable parameters, such as amount of concrete, θ_i are model parameters, and ε is a random variable that represents the model error. This formulation resembles the classical linear regression formulation (Rao and Toutenburg 1999; Groß 2003) and its appealing extension with Bayesian inference (Box and Tiao 1973), in which the model parameters θ_i are random variables. An example of this type of model to predict environmental impacts is:

$$E_{OC} = (73500 \cdot A_c \cdot \theta_c + 6500 \cdot A_s \cdot \theta_s + 12000 \cdot A_w \cdot \theta_w)\varepsilon_{OC} \quad \mathbf{(4.2)}$$

where E_{OC} is the energy (J) associated with the onsite construction phase of a building, A is a constant for the floor area (m^2) associated with a particular load bearing type, θ is a random variable for the parameter uncertainty, ε is the random variable representing the model error, and the subscripts c, s and w are used to distinguish load bearing type materials used, concrete, steel and wood respectively.

The two key questions in the development of models in the form of the Equation 4.2 are the selection of the model form and the determination of the θ variables. When data is available, the determination of the θ variables is done through the use of dimensionless explanatory functions, $h(x_1, x_2, \ldots)$, that result in dimensionless θ*'s*. The Bayesian updating scheme as presented by Box and Tiao (1973) provides probability distributions for the θ 's and the remaining model error, ε. By looking at different candidate explanatory functions and their coefficient of variation of the parameter theta, different schemes exist to decide which ones contribute more significantly and which may be excluded. In this thesis, the collection of data over a life cycle is not available, and detailed process data reported by Life Cycle Inventories represent a point estimate of pre-use or embodied effects. Thus, the approach taken in this thesis is to relax the boundary considerations and develop models for each life cycle phase that use engineering judgment to estimate the values of the parameters to develop probabilistic models to estimate each of the impacts of interest.

In summary, this thesis will formulate probabilistic models that receive random variables as input and produce a measure of environmental impact as output, with the properties previously discussed. Probabilistic models are a key step in the use of the reliability tools which can help determine the distributions of possible outcomes, the associated probabilities of exceeding certain values and the determination of importance vectors that can help direct design improvements. The models are implemented in the Rt software described in the next section.

4.1.2 Rt Software

Rt (Mahsuli and Haukaas 2009) is a state-of-the-art reliability software application developed at the University of British Columbia as part of the Infrastructure Risk Project (www.inrisk.ubc.ca). Rt is available for download, free of cost, for the Microsoft Windows and Mac OS X operating systems. The software provides a flexible, convenient and powerful interface to implement probabilistic models of the form described in the previous section, orchestrate analyses that utilize several models, evaluate limit state functions to calculate their probabilities of exceedance using reliability analysis algorithms, communicate with external software, handle and visually display spatial coordinates on a map, plot histograms through sampling algorithms and find importance vectors of modeled parameters. A screenshot of Rt is presented in Figure 4.3. The environmental impact models are included under the consequence models drop-down in the left-most objects pane.

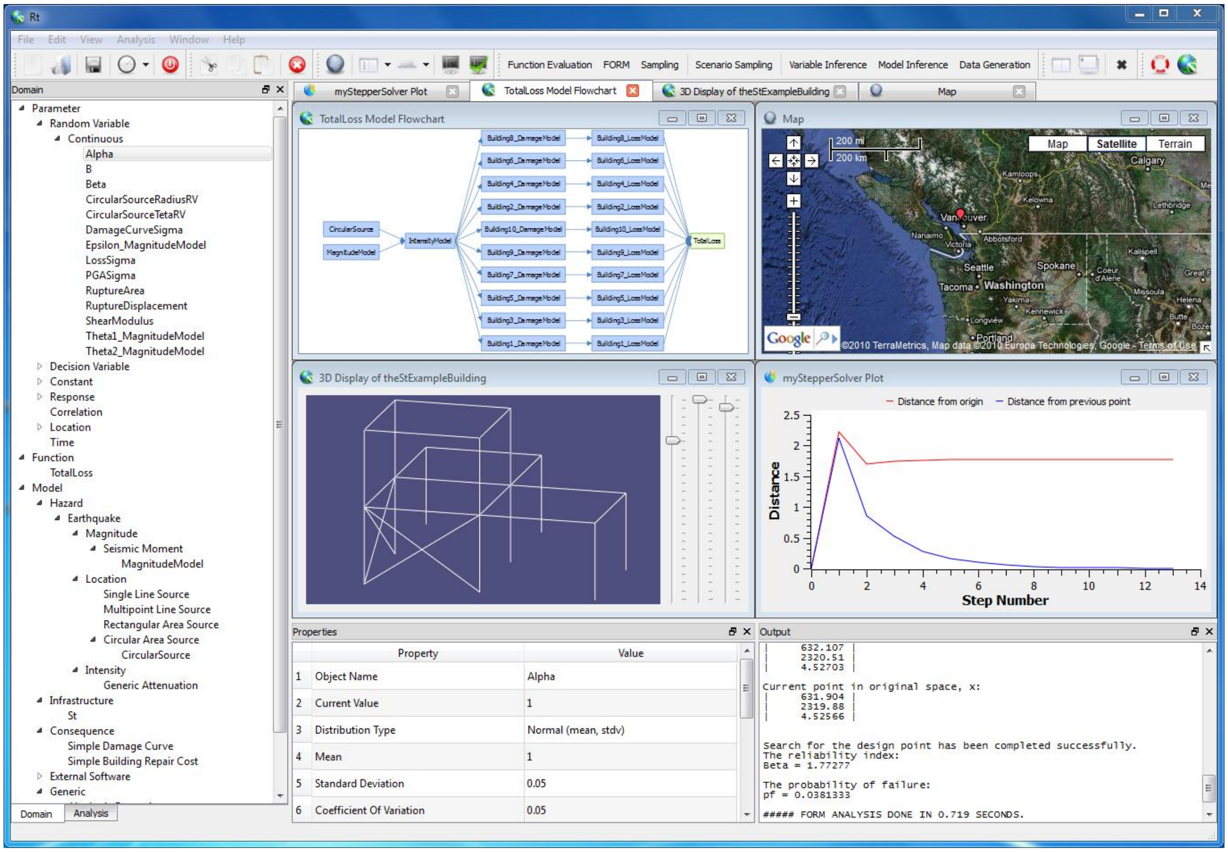

Figure 4.3 Screenshot of Rt software

4.1.3 Life Cycle Model Methodology

The different environmental impact models that will be presented in this chapter leverage the power of probabilistic models to allow the use of reliability tools in decision support. All models are heavily based on what will be called hereafter an "intensity" modeling strategy. The intensity variables relate a measurable variable, such as the quantity of construction material of a given type, or the number of worker hours, to each of the environmental impacts of interest. This practice follows closely the LCA methodologies that have been applied to buildings in other studies. However, the importance of the calculation and justification of these impact factors is made explicit in a way that requires direct use of engineering judgment. This is in direct contrast to traditional LCA approaches that often rely on a particular software tool and other "black box" approaches that rely more heavily on simplified assumptions that are less accessible to users.

4.1.4 Simplified Building Life Cycle

The conceptual basis of the life cycle of a building is developed in this section by defining in simple terms the different impact contributions that make up the life cycle of a building. The discussion will focus on the environmental impact of primary energy, but is equally applicable to the other impacts studied in this thesis (water and GWP).

The life cycle energy of a building can be calculated by adding the cumulative energy used at each life cycle stage as shown in Figure 4.4. In the simplified case scenario shown, the life of a building begins at construction time, t_0, when energy is used in the extraction and manufacturing, $E_{E\&M}$, of all building materials required as well as their on-site construction, E_{OC}. In reality, the energy used during the extraction, manufacture and on-site construction, occurs at different time intervals, but they are considered here to occur instantaneously at construction time, t_0 for simplicity.

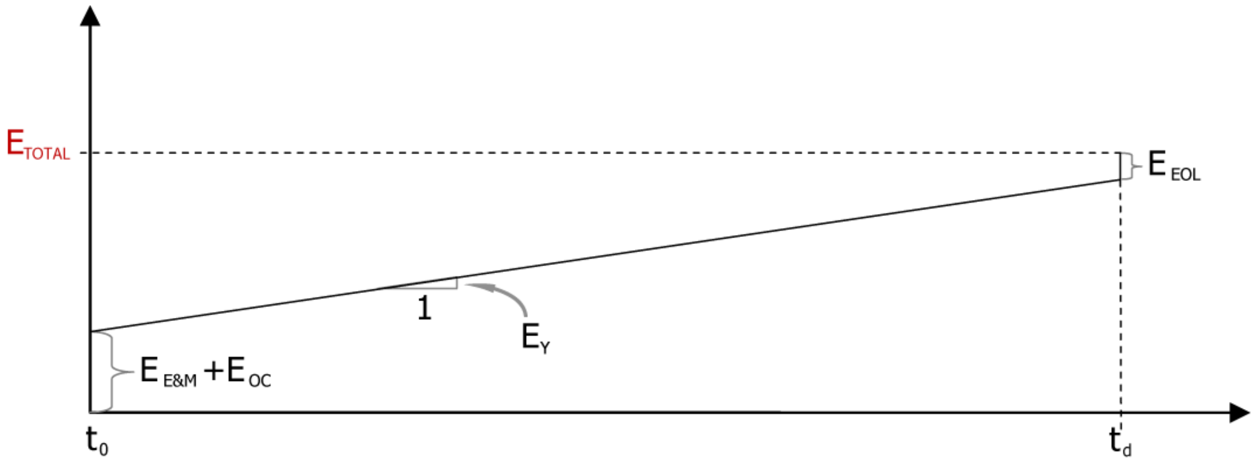

Figure 4.4 Simplified building life cycle energy usage

The building's life cycle then incurs additional annual energy usage during operation, E_Y, for the duration of the building's design life, t_d. Most of this energy usage is due to normal building activities, such as: heating water, space heating, space cooling, plug loads, lighting and others. In reality, the energy use is not a fixed value, but instead fluctuates for a given year that a building is operated. This is due to changes in a particular year's weather variations, changes in occupancy, construction of adjacent buildings (that may shade previous solar gain), occupant behaviour, purchase of new appliances, replacement of existing building systems, etc. For simplicity, however, the annual energy is shown as a constant linear increase.

The additional recurring energy demand over the operation phase of a building is due to maintenance and replacement of components that have life spans shorter than the building's design life, such as roof shingles or other materials such as paint, carpeting or piping if they are included in the analysis. These replacement operations have associated energy intensities due to their end of life and remanufacture. They also create a demand for new materials, which themselves have upstream impacts. For now, the replacement component is ignored in the figure and it is noted that it has been identified as a research gap in need of more attention by other researchers (Blengini and Di Carlo 2010). Another simplifying assumption is that the building does not suffer major renovations or expansions throughout its design life.

Finally, when the design life, t_d, of the building is reached, there is energy used or recovered in the end of life for the different building components. As pointed out previously, older studies have found the energy use during the end-of-life phase almost negligible, although it is recognized that this may not be the case for low energy buildings. Therefore, the cumulative value of the energy used during the building's life, E_{TOTAL}, can be calculated by adding the contributions from each one of the building's phases as shown in Eq. 4.3 where all variables have been previously defined.

$$E_{TOTAL} = E_{E\&M} + E_{OC} + E_Y \cdot t_d + E_{EOL} \quad \textbf{(4.3)}$$

One purpose of calculating this life cycle energy is to compare the energy performance of different design alternatives or to detect the life cycle phase with the greatest environmental impacts. Since the use of different materials has effects on operation, maintenance and end of life, the life cycle energy provides a fair indicator for comparison that could not be captured by analyzing only a subset of the life cycle stages. Keeping track of each type of energy, such as fuel source, is also useful to calculate other impacts such as GWP.

Since the desired framework would like to consider elements beyond buildings in the future, it is useful to think how this simplified model would be different at a regional scale, such as for network systems like roads, bridges, or underground water and wastewater distribution systems. In all of these cases, the model phases would be surprisingly similar, except for the operation and maintenance phase. At a regional scale, however, more care has to be taken to avoid double counting some of the environmental impacts. The design life of the water distribution system is also relevant as it is sensitive to hazards as evidenced by recent earthquakes (Reyallo 2010). In the use phase for a water distribution system it is necessary to estimate the energy input for operation, such as electrical demand from pumps used to convey water and—as regional analyses expand—it is necessary to take greater care to avoid double counting. The replacement energy during the operation phase, however, would likely consider direct and indirect impacts such as additional congestion, which produces additional energy and emissions. This model formulation would be similar when analyzing bridges or roads.

4.1.5 Sources of Data

Now that the idealized building life cycle model has been established, the sources of the data necessary to develop different energy, water and GWP intensity values are identified. The information required is, unfortunately, spread throughout a variety of sources. This has the consequence that the data obtained from different sources may be obtained from different years and may feature slight differences in methodologies. The ability to incorporate uncertainty, however, is particularly useful in ameliorating this situation.

Table 4.1 identifies sources that are particularly relevant to estimating intensities of the extraction and manufacturing phases. The data is offered in different formats and at different levels of detail, but they are all applicable to North America.

Table 4.1 Sources for energy, water and emissions data relating to extraction and manufacture of building materials

Source Name	Description / URL
Life Cycle Inventory Database	The National Renewable Energy Laboratory holds a collection of Life Cycle Inventories that is available after online registration. The data is constantly maintained, peer reviewed and can aid in the creation of full LCA studies. The data is specific to the United States and includes a wide range of data in standardized formats compatible with advanced

Source Name	Description / URL
	LCA software. Process data ranges from transportation to material production and is suitable for use in building LCAs. The data is most relevant to extraction and manufacture phases, although it is also applicable to transportation. The data obtained, however, is relevant to energy, resource and water flows, as well as discharges to air, water and land. http://www.nrel.gov/lci/database/default.asp
Athena Companion Life Cycle Inventories Database Reports	The Athena Institute offers several life cycle index reports, which are updated roughly every five years. Reports include materials such as concrete and steel as well as envelope materials such as insulation. Data is reported by region of Canada and transportation, electricity grid mix data, and other assumptions are documented. The reports are available in .pdf format which makes the extraction of relevant data a tedious process. In addition, reports are compiled at different years and by different organizations, but are freely accessible without registration. The data reported is relevant to energy, resource and water flows, as well as discharges to air, water and land. http://www.athenasmi.org/tools/impactEstimator/companionLCIDatabaseReports.html
Economic Input-Output LCA	The Green Design Institute at Carnegie Mellon University hosts this online tool. Based on the sectors of the economy, the tool offers economic data, as well as some environmental data for money spent in each sector. The latest revision allows searching for economic sectors of interest that best describe a process. Access is free, without registration, and study findings can be easily verified as they are all reproducible using the tool. The information from this database is useful for estimating upstream embodied energy, water and emissions of each life cycle stage, but requires information on the costs (rather than quantities) and to which economic sector they apply. http://www.eiolca.net/
Inventory of Carbon and Energy	The University of Bath maintains the Inventory of Carbon and Energy. After submitting an online registration, users are able to download a .pdf document containing an extensive list of embodied energy and carbon of different materials based on published analyses, although they are mostly relating to technologies used in the United Kingdom. The information is therefore useful for identifying values and variability of embodied (cradle to gate) energy and carbon. http://www.bath.ac.uk/mech-eng/sert/embodied/

Table 4.2 presents sources that are most relevant to estimating energy impacts during building

operation. Energy usage can be translated to GWP by making reasonable estimates on the proportion of the types of fuels used. Sources for water usage have only been found as regionally aggregated estimates that are not particularly useful for predictive purposes.

Table 4.2 Sources for energy data during the operation phase of a building

Source Name	Description / URL
American Society of Heating Refrigerating and Air Conditioning Engineers & Illuminating Engineering Society of North America Standard 90.1	The American Society of Heating Refrigerating and Air Conditioning Engineers, along with partner organizations, maintain several international standards relating to ventilation, energy use and occupant comfort. The document outlines acceptable calculation procedures for establishing a baseline building and creating energy savings. Energy savings can be met through prescribed criteria or through the justification using hourly energy models. Lighting densities for building types are also provided. http://www.ashrae.org/technology/page/548
Model National Energy Code of Canada for Buildings	The energy code is similar in purpose to the code mentioned above. Last update occurred in 1999. http://oee.nrcan.gc.ca/commercial/newbuildings/mnecb.cfm
Canadian Building Energy End-Use Data and Analysis Centre	The University of Alberta hosts this database which features reports and information regarding energy end-use data for buildings in Canada. Most information is accessible through reports. http://www.cbeedac.com/home/index.html
British Columbia Government	The government of British Columbia completed in 2009 a Greenhouse Gas Inventory report for the year of 2007. Tables are available regarding some of the emission factors for fuel consumption in a spreadsheet format. http://www.env.gov.bc.ca/cas/mitigation/ghg_inventory/
National Energy Use Database	Maintained by the Office of Energy Efficiency of Natural Resources Canada, this resource contains information on the building stock by region as well as end-use energy information collected through surveys. Additionally, some summary tables contain information indicating qualitatively the reliability of the data (i.e. acceptable, use with caution or too unreliable to be published). The information is therefore most useful for information on the building stock and the operational energy use by building type at an average level. http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/databases.cfm
Canada Green Building Council LEED v.1.0	Presents a method for estimating water usage reduction in new buildings, based on fixtures available and occupancy data. Information on the water

Source Name	Description / URL
Green Building Rating System for New Construction & Major Renovations	demand of standard fixtures is also included. http://www.cagbc.org/

It is possible to use annual energy estimates from publications like the ones listed in this table. The only complication with using annual energy-use estimates from the energy codes is that they may not be representative of innovative building technologies. Therefore, their use could obscure possibilities for improving building energy performance. As hinted by numerous studies cited in this thesis, the alternative for using published average annual energy usage is the creation of more detailed building energy simulation models using software such as eQuest or EnergyPlus. The input required by this operational energy modeling software varies. However, in general, it is much more detailed and requires the use of weather files or "typical year" weather, which contain representative information, such as hourly fluctuations in temperature, solar radiation and wind speeds for given locations. This is used by the software application to simulate the performance over a year and return estimates on energy use and fuel types. Some additional inputs of energy software include: location, detailed building shape, type and orientation, materials, material assembly of walls and roofs, window size, characteristics and orientation, occupancy and lighting fixture types among others. Table 4.3 suggests additional sources with different levels of detail that may be helpful in determining air emissions to calculate GWP, primarily for transportation. Transportation is relevant for most of the life cycle stages in a building.

Table 4.3 Sources useful in determining transportation air emissions during the building life cycle

Source Name	Description / URL
US EPA: AP-42	Separates emissions into two categories: stationary and mobile. Stationary sources are available through online reports, while the mobile sources are currently dealt through the use of a spreadsheets and other software available online. http://www.epa.gov/ttnchie1/ap42/
Nonroad	Developed by the Environmental Protection Agency, Nonroad is a model of air emissions of vehicles and non-vehicle mobile sources for past, present and future emissions. http://www.epa.gov/otaq/nonrdmdl.htm
Mobile 6	Mobile6 is the latest update to the vehicle based emission model. http://www.epa.gov/otaq/m6.htm
Energy Efficiency Trends Analysis Tables	Natural Resources Canada maintains a regional database on energy efficiency of transportation and other services. Some data is available by region and organized by year, beginning with the late 90's. http://www.oee.nrcan.gc.ca/corporate/statistics/neud/dpa/analysis_ca.cfm

Maintenance is primarily quantified through the replacement of components with life times shorter than the building's design life. There is little information available, as it is highly dependent on quality of installation, frequency of use and weather. Only a couple of studies, as presented in Table 4.4, have been found that are applicable in North America. Both studies lack information on the level of uncertainty and variability, although they indicate that the lifetime of some building components have changed over the years, at times being longer, and in some instances being shorter than they used to.

Table 4.4 Sources for maintenance and life expectancies of building products

Source Name	Description / URL
Athena Sustainable Materials Institute – Maintenance, Repair and Replacement Effects for Building	This report prepared by Morrison Hershfield Limited, contains detailed information on life expectancies of different construction materials, frequency of repair and energy used in repair, organized by different cities in Canada and the United States of America.

Source Name	Description / URL
Envelope Materials	http://www.athenasmi.ca/tools/impactEstimator/companionReports/Maintenance_Repair_And_Replacement.pdf
Study of Life Expectancy of Home Components	This report on residential life expectancies was prepared by the National Association of Home Builders and the Bank of America Home Equity. Most of the information is relevant to interior furnishings, flooring and doors. http://www.nahb.org/fileupload_details.aspx/?contentTypeID=3&contentID=51&subContentID=262451

Finally, very little is known about the environmental impacts during end of life. The studies by Blengini (2009) and Thormark (2006) are among the few published studies that have focused on the end of life of a building and construction and demolition waste.

4.2 Environmental Impact Model Library

This section contains proposed models to quantify the environmental impact of buildings throughout their life cycle. A format is used that first presents the applicable scope and then presents the model equation form and discusses its application. Table 1.1 provides a summary of the expanded scope encompassed by the models that will be presented in the following subsections.

Intensity variables are a key ingredient in the modeling strategy in this thesis. The intensity variables have units of environmental impact per respective unit. For example, in the energy models they may have units of J/kg, J/m^2, J/ton/km, while in the water model, they may have units of L (of water)/kg or L/m^2. The mean intensity value, and associated coefficient of variation, can be estimated from published Life Cycle Inventories, relevant Economic Input-Output LCAs, or even better: they may be developed from a detailed understanding of the extraction and manufacturing technologies used in producing a material. Therefore, while the model formulation is simplified by the use of intensity variables, a burden is placed on the analyst to select appropriate values for the intensity random variables. However, guidance is provided in the form of tabulated intensity values in this thesis and on the relevant pages of the Rt user's manual. This modeling approach is different from that taken by other tools, such as Athena's Impact Estimator, where the intensity variables still exist, but are inaccessible for the user. The advantage of the approach is that the user need not input additional data, but it has the disadvantage that the user is bound by simplifying assumptions that may not adequately represent the real building conditions. Another significant difference is that the methodology proposed here is probabilistic, while tools like Athena's Impact Estimator are deterministic. The environmental impact models from Rt are therefore more informative from a designer's perspective, as they provide an additional layer of information about the variability of the response instead of a point estimate.

The most important detail is to remain consistent in the development of these intensity values when carrying out an analysis. This can help alleviate problems such as double-counting impacts or inconsistent assumptions. It is emphasized that intensity values normally vary depending on the location of the project and the specific history of the material used. This includes information such as sourcing distances, technologies and fuel mixes to produce electricity.

4.2.1 Energy Building Models - Fine Detail

This section presents the models necessary to estimate at a fine level of detail the life cycle energy usage in a building. It is thus assumed that a fair amount of information about a building is available. The models will be introduced according to building phase and a discussion will follow on their implementation.

4.2.1.1 Extraction and Manufacturing Phase

The model that will be presented next addresses the elements of the scope shown in Table 4.5.

Table 4.5 Energy model for extraction and manufacture stage, fine detail

Impact	Life Cycle Phase	Scale	Detail
Energy	Extraction & manufacture	Building	Fine

The energy due to the extraction and manufacture phase of a building can be expressed as,

$$E_{EM} = E_p + E_t = \sum q i_p + \sum q i_t d = \sum q(i_p + i_t d) \quad \textbf{(4.4)}$$

where E_{EM} is the energy associated with the extraction & manufacturing phase of the materials considered in a building (J), E_p is the energy due to the extraction and processing of a material, E_t is the energy required to transport the material to the site, q is the quantity of a given material (i.e. concrete, wood and steel) in kg or relevant unit that is required in the building of interest, d is the distance travelled by each material, including backhaul (km), i_p is the process energy intensity for a given material's extraction and manufacture (J/kg), i_t is the transportation energy intensity for a given mode or mixes of freight transportation (J/kg/km). The quantity of a given material q should include the actual demand required by the building. Therefore, it is higher than the measured known quantity in a building or shown in building drawings. The quantity present should be increased by a "waste factor" to account for this difference.

It is deemed important to quantify explicitly the transportation to the site, as this value can make a difference in the environmental impact. Additionally, when reusing reclaimed materials from another site, transportation may be one of the only quantifiable impacts and therefore merits inclusion into the model. The reason to exclude the intermediate freight transport upstream of manufacture is that this is hard to estimate since the quantity of material produced may require a higher amount of raw material transported. For example, the production of one ton of Portland cement requires roughly 1.6 tons of raw materials.

Additionally, material quantities should be adjusted to reflect the fact that material is generally wasted during on-site construction. This occurs for a variety of reasons, such as lumber lengths not matching required lengths or cement that forms a film in the mixing truck container and is washed out. Table 4.6 presents an example of some energy intensities and waste factor values that have been assumed for construction materials in another study. The waste factor is expressed as a percentage of the material present in a building (i.e. from a building take-off). There is great variability within the literature on both intensity factors and waste factors.

Table 4.6 Sample energy intensity values, i_p, and waste factors for building materials

Material	Quantity unit	Energy intensity, i_p (MJ /unit)	Waste factor (%)	Location of study and source
Concrete (K30)	kg	0.83	1.5	Sweden, (Gustavsson et al. 2010)
Steel		19.8	15	
Polystyrene		90.11	7	

Additionally, the model considers transportation intensities and distances from producer to the site. This is usually called freight transport and data is available at various sources for energy use and GWP while very little is known about water intensities of transportation. Table 4.7 shows some energy intensity values for freight transport (Natural Resources Canada 2010). The GWP intensity estimates were developed assuming diesel fuel for trucks and rail, and heavy fuel oil for vessels by using additional sources for the energetic density of fuels and emission factors (British Columbia Government 2009).

Table 4.7 Example energy and GWP intensities of freight transport for year 2007 in Canada

Mode	Transportation Energy Intensity i_t, J/kg/km	Transportation GWP Intensity i_{gt}, kg CO2e/kg/km
Truck transportation	3210	0.00023
Light truck (0-4 tons)	7640	0.00054
Medium trucks (4-15 tons)	6600	0.00047
Heavy trucks (+15 tons)	2400	0.00017
Rail	230	0.00002
Marine	430	0.00003

4.2.1.2 On-Site Construction Phase

The energy used in the on-site construction phase of a building's life cycle has been determined to be a small percentage of the entire life cycle energy in other studies. However, due to the support for a predictive analysis put forward in this thesis, a model is proposed for estimating the energy use during this phase. Some key variables that affect the energy usage during this building stage are the complexity of the construction, the type of machinery used and the size of the project. Table 4.8 describes the scope of the proposed model.

Table 4.8 Energy model for on-site construction stage, fine detail

Impact	Life Cycle Phase	Scale	Detail
Energy	On-site construction	Building	Fine

The proposed model for estimating the energy during on-site construction is:

$$E_{OC} = r_h t_{wh} i_{hm} + (1 - r_h) i_m t_{wh} + \frac{1}{t_s} t_{wh} i_{wt} d_{wt} n_w \quad \textbf{(4.5)}$$

where E_{OC} is the energy associated with the on-site construction phase of a building (J), r_h is the ratio of worker-hours allocated to the use of heavy machinery (such as cranes, bulldozers, backhoes) to the total worker hours, t_{wh} is the total worker-hours allocated to construction and site work, t_s is the worker shift (hours), typically 8 hours, d_{wt} is the distance travelled by workers including return trips (km), i_{hm} is the energy intensity due to heavy machinery use (J/worker-hour), i_m is the energy intensity due to manual labour (J/worker-hour), i_{wt} is the worker transportation energy intensity (J/passenger/km) and n_w is the number of workers during construction.

Worker transportation is included in this model since it is an activity that is caused by the construction of a building, and it would be hard to argue that such transportation demand would have occurred without the need for the construction operation. Additionally, this offers a decision variable that is highly variable depending on the prevalent mode of passenger transport used by workers, which can also be modified through the use of incentives from the construction crew employer. Table 4.9 summarizes some published values for passenger transportation in British Columbia (Poudenx and Merida 2007).

Table 4.9 Sample passenger transportation intensity values in British Columbia (Poudenx and Merida 2007)

Mode	i_{wt}, J/passenger/km	i_{gwt}, kg CO2e/pkm
Light-duty Truck	3,560,000	0.286
Automobile	2,730,000	0.220
SeaBus	1,840,000	0.164
Diesel bus	920,000	0.105
West Coast Express	570,000	0.048
Trolley bus	410,000	0.0025
SkyTrain	390,000	0.0024

From a regional scale perspective, some indirect effects caused by on-site construction, such as traffic delay due to construction or maintenance operations that restrict flow of vehicles (particularly during peak travel hours) would cause an increase in energy and should be accounted for in regional applications of this model.

4.2.1.3 Building Operation Phase

The operation phase of buildings uses energy to provide the necessary conditions that facilitate the activities performed in a building. The following model estimates the energy for the building operation stage as outlined in Table 4.10 .

Table 4.10 Energy model for building operation stage, fine detail

Impact	Life Cycle Phase	Scale	Detail
Energy	Operation	Building	Fine

The main sources of energy usage during building operation in Canada vary depending on the primary activity carried out in a building, sometimes referred to as building type (i.e. single family residential, multi-unit residential, school, restaurant etc.) In general, the main energy demands during operation are space conditioning (heating and cooling), domestic hot water heating, lighting, and increasingly plug loads (from appliances and electronics). The proposed model, at this level of detail, relies on exterior building energy software, historic billing data or engineering judgment to determine a reasonable value for the annual energy usage. This value is then propagated annually for the design life of a structure.

The model for estimating energy during building operation is,

$$E_O = t_{des} E_a \quad \textbf{(4.6)}$$

where E_O is the total energy used for operating a building over its life cycle (J), E_a is the annual energy demand (J/year) and t_{des} is the expected design life of the building (years).

As mentioned, for a new building, a separate building energy model using energy modeling software (eQuest, Energy Plus, ESP-r, IES VE, etc.) can help determine realistic estimates on a case by case basis for new buildings. There are numerous inputs into a building energy model such as building location, orientation and type of envelope surfaces, occupancy schedules, conditioned volumes, materials and heating, ventilation, air conditioning and lighting technologies used. The development of a refined probabilistic model that simulates the dynamic interaction of hourly climate and occupancy is believed to be best handled through the use of the existing software listed above, although the development of a more simple model is proposed for the coarse version of this model in the coarse detail section, when limited information is available or where a regional first order analysis is required.

4.2.1.4 Maintenance Phase

The maintenance phase of a building creates a recurring energy demand over the life of a structure when materials with life spans shorter than the building itself are replaced. There is great uncertainty and little existing research on the service life of different materials. It has been previously suggested that the replacement is not necessarily prompted by a no longer functioning component, but at times due to changes in style, which is particularly true of painted surfaces and flooring. A model reflecting the one proposed by Adalberth (1997a), is presented, and a renewed call for more research in this area is made, (Blengini and Di Carlo 2010; Adalberth 1997a) . Table 4.11 presents the scope of the model presented.

Table 4.11 Energy model for building maintenance stage, fine detail

Impact	Life Cycle Phase	Scale	Detail
Energy	Maintenance	Building	Fine

The model for estimating energy due to building maintenance is of the form,

$$E_M = \sum \left(\frac{t_{des}}{t_{mat}} - 1 \right) i_{mat} \ , \quad t_{mat} < t_{des}$$
$$E_M = 0 \ , \ t_{mat} \geq t_{des} \qquad \textbf{(4.7)}$$

where E_M is the energy associated with the maintenance phase of a building (J), t_{des} is the design life of building (years), t_{mat} is the design life of the assembly of interest (years), and i_{mat} is the energy intensity of each assembly of interest (J/replacement).

Replacement usually takes place for assemblies, such as cladding or windows, which are a combination of materials (for instance in windows this could be the glazing, sealants and an aluminum frame). Thus, a reasonable approximation would combine material quantities as reported in previous models to determine a reasonable intensity for an assembly considered that additionally accounts for installation and end of life for the assembly replaced. Table 4.12 provides values that have been reported in other studies regarding the replacement needs of different assemblies.

Table 4.12 Life spans of materials used in construction

<table>
<tr><th>Building element</th><th>Life span (years)</th><th>Country, Source, Notes</th></tr>
<tr><td>Life span of building</td><td rowspan="5">t</td><td rowspan="13">Sweden, (Adalberth 1997a),
t in the study was 50 years for a residential project</td></tr>
<tr><td>Frame (ext. walls, int. walls, joists, foundation, insulation)</td></tr>
<tr><td>Parquet flooring</td></tr>
<tr><td>Water pipes and electric wires</td></tr>
<tr><td>Ventilating channels</td></tr>
<tr><td>Facing, wooden paneling</td><td rowspan="4">0.6t</td></tr>
<tr><td>Windows and doors</td></tr>
<tr><td>Wardrobes and cupboards</td></tr>
<tr><td>Roofing tiles and drainpipes</td></tr>
<tr><td>Plastic carpeting</td><td>0.34t</td></tr>
<tr><td>Water heater</td><td>0.32t</td></tr>
<tr><td>White goods</td><td>0.24t</td></tr>
<tr><td>Painting and wallpapering</td><td>0.2t</td></tr>
<tr><td>Shell components:
Basement, Garage, Floors and stairs, interior walls, Roof, Terrace, Windows and Doors, Surface lining, Flooring, Insulation</td><td>t</td><td rowspan="2">Italy, (Blengini and Di Carlo 2010), t in the study was 70 years for a residential project</td></tr>
<tr><td>Plants:
Water plant, Heating Ventilation and Air Conditioning, Lighting, Ventilating</td><td>0.5t</td></tr>
</table>

Building element	Life span (years)	Country, Source, Notes
Building shell and structure	(0.27, *t*)	USA, (Scheuer et al. 2003), *t* in the study is 75 years for a university building. More detail is provided in their paper, ranges are reported here for conciseness
Mechanical, electrical, plumbing	(0.27*t*, *t*)	
Building interior and finishes	(0.07*t*, *t*)	

As seen in the table, there is little agreement on the replacement nature of building materials, although arguably, this could be due to regional variations in construction. Additionally, the replacement lives of some elements are strongly dependant on proper recurring maintenance. Maintenance is thus an area that deserves more research in the life cycle study of buildings.

It is also important to note that a significant amount of the damage during hazards like earthquakes occurs in greater proportion to non-structural components (i.e. glass in windows, cracks in partition walls) and even structural elements. Therefore, quantifying properly the maintenance impacts of buildings requires structural design that can withstand hazards and mitigate damage to building structural/non-structural elements and components.

A future refinement of this framework would be to link the occurrence of an earthquake to a degree of damage, which can be translated to a quantity of these vulnerable structural and non-structural components in a building that would require replacement and associated upstream environmental impacts. This is an issue that concerns structural engineers directly, as proper design of a structure, particularly performance-based (here used in the structural sense of preventing excessive deflections), can greatly mitigate building damage.

4.2.1.5 End of Life Phase

The end of life phase of a building has been treated in various ways in other life cycle studies. Some studies neglect the end of life phase, while others assume that materials are demolished and transported to a landfill, and very few other assessments have considered alternate scenarios like recycling and energy recovery. In general, it is a controversial estimate since it is believed to happen in a distant future (generally around 50 years after initial construction), and it is unknown what the actual situation may be. Even if a building is designed to be disassembled, that is no guarantee that it will be. In Europe, legislation has forced the construction industry to seek destinations other than landfills for demolished materials. The model presented hereafter attempts to capture the possibilities for end of life of the recoverable materials in a building. It is well known, that a great part of the materials, at the end of life of a building, end up in the landfill. Table 4.13 identifies the scope of this model.

Table 4.13 End of life phase energy model, fine detail

Impact	Life Cycle Phase	Scale	Detail
Energy	End of life	Building	Fine

The equation for estimating the energy at the end of life of a building is,

$$E_{EoL} = q_{total} i_{eol} \tag{4.8}$$

where E_{EoL} is the energy associated with the end of life phase of a building (J), q_{total} is the total building material mass (kg), i_{eol} is the energy intensity of the building at the end of life (J/kg).

The end of life phase is problematic with respect to how the benefits and burdens are distributed. More research is required to understand the relevant benefits of each end of life option and quantify them in this framework. Intuitively, it would be expected that intensities for reusing should be lower than those for recycling, and perhaps less than those for disposing in a landfill, but the conditions required for this need to be further examined.

Life cycle models for each environmental impact and each life cycle stage have been introduced for the case of detailed data being available. As detailed data is not always available, the following section introduces alternate models that require less detailed data to produce similar life cycle estimates.

4.2.2 Energy Building Models - Coarse Detail

Coarse detail models are presented in this section to facilitate a preliminary analysis that may be required for large regions containing many buildings where information such as quantities of concrete or steel are unavailable. Furthermore, it is recognized that many times, the exact quantity of materials is not known and is expected to vary among different buildings depending not only on their original construction date, but also on their maintenance schedule, which is many times also unknown. This presents both a challenge and an opportunity when analyzing existing buildings, which are the dominant portion of the building stock of cities. Through the use of the models in this section, an estimate of the building's life cycle can be made.

4.2.2.1 Pre-Use Phase

Since coarse detail data is believed to be available, it is convenient to combine the extraction, manufacture, intermediate transportation and on-site construction phases into a single "pre-use" phase.

Table 4.14 identifies this model scope. The explanatory variables chosen are related to the main force resisting system of a structure, floor area and energy intensity.

Table 4.14 Energy model for pre-use phase, coarse detail

Impact	Life Cycle Phase	Scale	Detail
Energy	Extraction & Manufacture On-site Construction	Building	Coarse

The pre-use phase, energy can be estimated as,

$$E_{PU} = a_f (n_s i_{pu} + i_p) \quad \textbf{(4.9)}$$

where E_{PU} is the energy associated with the extraction, manufacturing and on site construction phases of a building (J), a_f is the building's footprint area (m^2), n_s is the number of stories, i_{pu} is the energy intensity for the pre-use phases (J/m^2) and i_p is the intensity for the presence of underground parking (J/m^2 of parking).

The model reflects a low level of knowledge of a building that could be easily approximated from aerial photos or satellite imagery or a street view. Future refinements may consider correcting for geometrical effects that may be associated with higher energy use during construction.

4.2.2.2 Operation Phase

The operation phase is approximated in this model through the use of Heating Degree Days. Therefore the assumption is made that a building's energy usage is highly dependent on the climate of the region. The scope of the model presented is summarized in Table 4.15 .

Table 4.15 Energy model for operation, coarse detail

Impact	Life Cycle Phase	Scale	Detail
Energy	Operation	Building	Coarse

The proposed model is,

$$E_O = t_{des}\left(\frac{24(3600)(A(r_{ww}U_{win} + (1-r_{ww})U_{wall}) + 0.33NV)D_{HDD}}{\eta}\right) \quad \textbf{(4.10)}$$

where E_O is the energy associated with the operation phase of a building (J), U_{wall} is the total wall thermal transmission coefficient (W/m^2/K), U_{win} is the window assembly thermal transmission coefficient (W/m^2/K), r_{ww} is the window to wall ratio, N is the number of air changes per hour (ach), D_{HDD} is the heating degree days using the building's reference temperature (K days for reference temperature), η is the overall heating efficiency, V is the total air volume in building (m^3), and A is the surface area of the building exterior (m^2), 24 is used to convert from days to hours and 3600 is used to convert from Watt-hours to Joules.

The orientation of building (glazing) is related to solar heating gains, which are not considered in this model. Additionally, solar heat gain control strategies such as sun shades, fins or recessed windows are not accounted for by this model form. Further detail refinement of this model may significantly increase the number of variables. Cooling degree days may also be included in future refinements of this model to account for energy use in cooling.

4.2.2.3 End of Life phase

The end of life phase model for coarse data is presented in this section. Table 4.16 summarizes the scope of the model.

Table 4.16 Energy model for end of life phase, coarse detail

Impact	Life Cycle Phase	Scale	Detail
Energy	End of Life	Building	Coarse

The proposed model for estimating energy use in the end of life phase of a building is,

$$E_{EoL} = n_s a_f i_{eol} \quad \textbf{(4.11)}$$

where E_{EoL} is the energy associated with the end of life phase of a building (J), a_f is the building footprint area (m^2), n_s is the number of stories, and i_{eol} is the energy intensity of end of life for a respective structural system (J/m^2).

This model is based on the assumption that the intensity of demolishing and deconstructing varies depending on the primary structural system type. This is considered reasonable, as the material used in each structural system has different characteristics that make it easier to up-cycle, down-cycle or recover energy through use as fuel or dispose in a landfill.

4.2.3 Water Usage Building Models – Fine Detail

The models proposed in this section facilitate the estimation of the life cycle water usage in buildings. Water usage is highly dependent not only on available fixtures but also on building occupant behaviour.

The proposed model for life cycle water is formulated in a similar fashion to the life cycle energy model presented. While there are a number of buildings currently being designed for net-zero energy, much fewer are being designed for net-zero water. These net-zero designations generally only apply to the operation phase of a building's life cycle. Thus, it is likely that the bulk of the life cycle water demand will be a result of the building operation phase. Water usage models for the operation of a building are generally simplistic. The embodied water effects, however, are treated exactly as before, with the use of Life Cycle Inventories that relate quantities of material with their associated water demand.

The water usage during operation is a function of both the installed fixtures (rated by number of litres per flush, or time unit) and the actual use by building occupants. Generally, the actual use of each fixture is determined on a per user basis and then multiplied by the number of building occupants. As occupancies vary for different building types, the number of working or occupied building hours must be estimated. This is sometimes referred to as an occupancy schedule.

4.2.3.1 Extraction and Manufacture Phase

The model presented here estimates the water during extraction and manufacturing phase of construction materials. The scope is summarized in Table 4.17 .

Table 4.17 Water model for extraction and manufacturing phase, fine detail

Impact	Life Cycle Phase	Scale	Detail
Water	Extraction & Manufacturing	Building	Fine

The model proposed for estimating water usage during the extraction and manufacturing phase can be expressed as:

$$W_{EM} = W_p + W_t = \sum q i_{wp} + \sum q i_{wt} d \qquad \textbf{(4.12)}$$

where W_{EM} is the water associated with the extraction & manufacturing phase of the materials considered in a building (L), W_p is the water associated with the extraction and processing of materials (L), W_t is the water associated with the transportation to the construction site, q is the quantity of a given construction material (i.e. concrete, wood and steel in kg), d is the distance travelled by each material, including backhaul (km), i_{wp} is the process water intensity for a given material's extraction and manufacture (L/kg), i_{wt} is the transportation water intensity for a given mode of transportation to deliver the materials to the construction site (L/kg/km).

The water model follows the formulation proposed for estimating energy at the same life cycle stage. Unlike energy, water is still expected to be dominant during the building operation phase regardless of water reduction techniques used. This is due to the normal water demand needs that exist in buildings and which can only be supplemented through the collection of rainwater or the reuse of grey water.

4.2.3.2 On-Site Construction Phase

This section contains the model for estimating the water use during on-site construction of a building. The model scope is summarized in Table 4.18 .

Table 4.18 Water usage during on-site construction, fine detail

Impact	Life Cycle Phase	Scale	Detail
Water	On-Site Construction	Building	Fine

The model is of the form,

$$W_{oc} = t_{wh} w_{ioc} \tag{4.13}$$

where W_{oc} is the water demand during on-site construction (L of water), t_{wh} is the total worker hours required to complete construction activities and w_{ioc} is the water intensity (L of water/worker hour).

4.2.3.3 Operation Phase

This section presents a model for estimating the water usage during the operation phase of buildings. As stated, earlier, it is expected that the operation phase accounts for most of the life cycle water demand due to the length of time the building operates. The model scope is summarized in Table 4.19.

Table 4.19 Water usage during operation, fine detail

Impact	Life Cycle Phase	Scale	Detail
Water	Operation	Building	Fine

The water use during the building operation stage can be estimated by,

$$W_{op} = t_d d_{yo} o_e \left(i_{fl} + i_{mf} r_{mf} + i_{ff} (1 - r_{mf}) \right) \tag{4.14}$$

where W_{op} is the water demand during operation phase (L), t_d is the design life of the building (years), d_{yo} is the days of yearly operation of the building (for example, if the building is operated only 200 out of 365 days in a given year, d_{yo} is equal to 200 days per year), o_e is the total number of building occupants, i_{fl} is the water demand for each flow fixture (L/occupant/day), i_{mf} is the daily water demand for male occupants for each flush fixture (L/male/day), r_{mf} is the ratio of male occupants to total building occupants: normally 0.5 males to total building occupants, and i_{ff} is the daily water demand for female occupants for each flush fixture (L/female/day).

The model does not currently consider water usage for drinking, cooking or cleaning and leaks in fixtures, but captures the main water demands of a building. The water demand model introduced is helpful to introduce uncertainty by characterizing the water intensity values as random variables. The daily water demand can be developed by using the fixture information presented in Table 4.20 (Canada Green Building Council 2004). Normal assumptions are that there are a total of 9 uses per female per day and 6 uses per male per day for flush fixtures and 1 use per day for shower fixtures. The normal duration of uses for flow fixtures are also included in Table 4.20. The values are assumed for an 8-hour office day. Using for residential applications, one must make a reasonable estimate as to the time spent in the home and the number and duration of uses.

Table 4.20 Fixture and use information per day (adapted from Canada Green Building Council 2004)

Flow Fixture			Flush Fixture	
Fixture	**Water Demand (L/min)**	**Duration (min)**	**Fixture**	**Water Use (L/flush)**
Normal lavatory	9.5	0.25	Conventional WC	6.0
Low-flow lavatory	6.8	0.25	Low-flow WC	4.0
Kitchen sink	9.5	0.25	Ultra low-flow WC	8.0
Low-flow kitchen sink	6.8	0.25	Composting toilet	3.8
Normal shower	9.5	5.0	Conventional urinal	1.9
Low-flow shower	6.8	5.0	Waterless urinal	0.0
Hand wash fountain	1.9	0.25		

4.2.3.4 Maintenance and End of Life Phases

The maintenance and end-of life phases for water demand are neglected at present due to lack of data. It is estimated that the need for water for these activities is minimal. However, it is recognized that water is sometimes used during demolition to prevent excessive particulate and dust dispersal. This still remains a short-lived water demand when compared to the entire life cycle. Furthermore, adequate maintenance plays a key role in eliminating leaks in fixtures, an activity which should be accounted for in future models.

4.2.4 Water Usage Building Models - Coarse Detail

The operation plays a key aspect in the life cycle use of water in a building. For that reason, it is believed that the water demand may be estimated for the entire life cycle approximately if the building function is known

4.2.4.1 Entire Life Cycle

The model to evaluate the life cycle water usage is proposed in this section. The scope is summarized in Table 4.21 .

Table 4.21 Entire life cycle water usage, coarse detail

Impact	Life Cycle Phase	Scale	Detail
Water	Extraction & Manufacture On-site construction Operation End of life	Building	Coarse

The model for estimating the entire life cycle water usage can be expressed as,

$$W_{LC} = n_s A_f (w_{pud} + t_d w_d) \quad \textbf{(4.15)}$$

where W_{LC} is the life cycle water demand (L), n_s is the number of storeys in a building, A_f is the building footprint area of building (m^2), t_d is the design life of the building (years), w_{pud} is the water intensity of the materials used (pre-use) for a corresponding building function (L/m^2), w_d is the annual water intensity for a given building operation type ($L/m^2/year$).

The annual water intensity is formulated to accommodate mixed-use buildings that may have different areas serving different purposes (i.e. 1000 m^2 of retail space and 2000 m^2 of office space). It is an educated guess that certain building functions (i.e. coffee shop vs. school) require more water than others and more research is needed to develop better estimates.

4.2.5 Global Warming Potential – Fine Detail

4.2.5.1 Extraction and Manufacture Phase

An estimation of the life cycle GWP follows similar formats to the water and energy models for the extraction and manufacture stage. The proposed model scope is summarized in Table 4.22.

Table 4.22 Global warming potential for extraction and manufacture, fine detail

Impact	Life Cycle Phase	Scale	Detail
GWP	Extraction & Manufacture	Building	Fine

An equation for estimating the GWP for a building's extraction and manufacturing stage is,

$$GWP_{EM} = q\sum i_{gp} + i_{gt}d \qquad \textbf{(4.16)}$$

where GWP_{EM} is the resulting GWP from the extraction and manufacturing phase of a building (kg CO_2e), q is the quantity of a given material (kg), i_{gp} is the GWP intensity of a given material (kg of CO_2e/ kg of material), d is the transportation distance to the construction site including backhaul (km) and i_{gt} is the GWP intensity of the transportation mode used (kg CO_2e/kg of material/km).

4.2.5.2 On-Site Construction Phase

An estimation of the life cycle GWP follows similar formats to the water and energy models for the on-site construction phase. The proposed model scope is summarized in Table 4.23.

Table 4.23 Global warming potential for on-site construction, fine detail

Impact	Life Cycle Phase	Scale	Detail
GWP	On-Site Construction	Building	Fine

An equation for estimating the GWP for a building's on-site construction stage is,

$$GWP_{OC} = E_{OC}i_{gc} \qquad \textbf{(4.17)}$$

where GWP_{OC} is the GWP generated during the on-site construction phase (kg CO_2e), E_{OC} is the energy used during on-site construction (J) and i_{gc} is the GWP intensity of the on-site construction phase (kg CO_2e/J).

4.2.5.3 Operation Phase

An estimation of the operation phase is proposed in this section. The model scope is summarized in Table 4.24.

Table 4.24 Global warming potential for building operation, fine detail

Impact	Life Cycle Phase	Scale	Detail
GWP	Operation	Building	Fine

An equation for estimating the GWP for a building's operation stage is,

$$GWP_{OP} = E_{OP} i_{go} \quad \textbf{(4.18)}$$

where GWP_{OP} is the GWP generated during the building operation phase (kg CO_2e), E_{OP} is the total energy used during building operation phase (J) and i_{gc} is the GWP intensity of the energy used during the building operation stage (kg CO_2e/J).

4.2.5.4 End of Life Phase

An estimation of the end of life phase is proposed in this section. The model scope is summarized in Table 4.25.

Table 4.25 Global warming potential for end of life, fine detail

Impact	Life Cycle Phase	Scale	Detail
GWP	End of Life	Building	Fine

An equation for estimating the GWP for a building's end of life stage is,

$$GWP_{EoL} = E_{EoL} i_{geol} \quad \textbf{(4.19)}$$

where GWP_{EoL} is the GWP generated during the end of life phase (kg CO_2e), E_{EoL} is the total energy used during end of life phase (J) and i_{geol} is the GWP intensity of the energy used during the end of life stage (kg CO_2e/J).

4.2.6 Global Warming Potential – Coarse Detail

4.2.6.1 Entire Life Cycle

An estimation of the entire building life cycle GWP is considered useful for a case where little information is available. The proposed model scope is summarized in Table 4.26.

Table 4.26 Global warming potential for entire life cycle, coarse detail

Impact	Life Cycle Phase	Scale	Detail
GWP	Extraction & Manufacture On-site construction Operation End of life	Building	Coarse

An equation for estimating the GWP for a building's life cycle is,

$$GWP_{LC} = i_n(E_{total} - E_{OP}) + E_{OP}i_{op} \tag{4.20}$$

where GWP_{LC} is the life cycle GWP on a time horizon of 100 years (kg of CO_2e), i_n is the GWP intensity of non operational phases (kg CO_2e/ J), E_{total} is the entire life cycle energy for a building (J), E_{OP} is the total energy used over the operation stage of building's life cycle (J), i_{op} is the GWP intensity of energy used in the operation phase (kg CO_2e/J).

Depending on how the renewable technologies are treated in the analysis, they may result in negative intensity factors (i.e. by nature of treating materials whose energy can be recovered, like wood, as avoided fossil fuel impacts).

5 Example

An example is presented to demonstrate the methodology proposed in the previous section. The project used as an illustration of the methodology is a four-bedroom, two-storey, detached, single-family, wood-frame home in Ottawa, Canada. It is used as a base case in a PhD dissertation at the University of Toronto (Zachariah 2003). The house was built to the energy efficient R2000 standard in 1998. The original study created alternate, functionally equivalent versions of the home using steel and concrete structural frames. The analysis in this thesis will focus on the base-case wood framed home only. This house was selected because material quantities and building energy simulation results were available, which supports the application of the fine detail data quality models presented earlier.

5.1 Assumptions

When information is not available, as would be expected in some of the on-site construction and end of life phases, reasonable values are assumed and documented. In terms of assigning statistical distributions to intensity values, this thesis assigned coefficients of variation of 10% to values that are believed to be highly variable and 5% to those that reflect consistent agreement from previous studies. In all cases, the GWP Intensity values have been subjected to a 20% coefficient of variation, as estimates are believed to be quite uncertain. It is assumed that all intensity values follow a lognormal distribution, which prevents negative intensity realizations during the reliability analysis. The values used in the detailed models are obtained from the embodied energy and carbon dioxide values reported in the Inventory of Carbon and Energy (Hammond and Jones 2008). The original study by Zachariah (2003) was performed using Athena's Impact Estimator and HOT2000, a building energy simulation program. Thus, it is helpful to use the Inventory of Carbon and Energy as it is a freely available document (Hammond and Jones 2008). Additionally, for estimating transportation intensities, the National Renewable Energy Laboratory Life-Cycle Inventory database was used along with standard energy density values. When information was not available in the literature and assumptions could not be made, intensities were set to zero. The assumption of a design life of 35 years is kept and input as a constant, although the analysis would allow other distributions (including a uniform distribution).

Since the implementation in the Rt software requires the explicit input of statistical parameters, namely the distribution type and its properties (i.e. mean and coefficient of variation), there is a high degree of transparency when performing an analysis of this type. It is desired that as more data is collected for determining the values of energy and other impact intensities, it will be possible to confirm the nature and degree of the variability for each material. It is also desired to provide the sample-building example to stimulate discussion on the development of intensity factors and their use in this methodology.

5.2 Detailed Model Inputs

The quantities reported for the base case house are for the "as built" home. The quantities of materials are therefore increased using assumed waste factors and converted to mass values when required. For example, it is known from the Athena Concrete LCI documents (Athena Institute 2010a), that the 20MPa concrete is assumed to have a density of 2334 kg/m^3. This adjusts the value reported by Zachariah of 43.74 m^3, first to 45.93 m^3 as a consequence of assuming a 5% waste factor and then to 107,194 kg based on the reported density. Table 5.1

summarizes the material quantities from the original study and the final quantity of material for use in the subsequent detailed models.

Table 5.1 Original material quantity conversion assumptions

Material	Unit	Reported Quantity (unit)	Conversion (kg/unit)	Waste Factor (%)	Final Quantity (kg)
Concrete 20MPa	m^3	43.74	2334	5	107194
Mortar	m^3	6.82	1277	10	9580
Nails	ton	0.29	1000	5	305
Welded Wire Mesh	ton	0.12	1000	5	126
Wide Flange Sections	ton	1.86	1000	2	1897
Rebar, Rod, Light Sections	ton	1.37	1000	5	1439
Cold Rolled Sheet	ton	0.05	1000	2	51
Galvanized Sheet	ton	0.17	1000	2	173
Small Dimension Softwood Lumber, kiln dried	Mbfm	8.49	725	5	6463
Softwood Plywood	Msf	9.44	335	5	3321
Large Dimension Softwood Lumber, kiln dried	Mbfm	3.56	725	5	2710
Batt fibreglass (1")	m^2	4338.96	0.6	5	2734
6 mil Polyethylene	m^2	530.45	0.143	5	80
½" Regular Gypsum Board	m^2	569.53	0.4715	8	290
5/8" Regular Gypsum Board	m^2	398.76	0.4773	8	206
Brick	m^2	201.45	120.7	4	25288
Aluminum	ton	0.36	1000	2	367
Vinyl Siding	m^2	1421.31	0.85	5	1269
Glazing Panel	ton	42	1000	0	42000
EPDM Membrane	kg	163.81	1	2	167
Low E Tin Argon Filled Glazing	m^2	48.28	Omitted		
Joint Compound	ton	0.97			
Paper Tape	ton	0.01			
Water Based Latex Paint	L	490.08			

As stated previously, the embodied energy estimates are obtained from the freely available Inventory of Carbon and Energy (Hammond and Jones 2008). Since the Rt implementation is separated by primary material categories: concrete, steel, wood, gypsum wall board, vapour barrier, insulation, glass and other, the quantities were grouped accordingly and intensities were calculated using weighted averages (by mass). Table 5.2 summarizes the intensity values selected and the distribution parameters input into the Rt program. The material quantities were input as constants and the intensities as lognormal distributions with the properties identified in the table. Water intensity values were not readily available, so they were omitted in the analysis.

Table 5.2 Quantity and intensity values used as Rt input

Rt Model Material Category	Materials included	Quantity (kg)	Mean Energy Intensity (J/kg)	Mean GWP Intensity (kg CO2e)	Mean Water Intensity (L)	Coefficient of Variation (%) Energy, GWP
Concrete	Concrete 20MPa, Mortar	116,774	885,942	0.11	-	5, 20
Steel	Nails, Welded Wire Mesh, Wide Flange Section, Rebar, Rod, Light Sections, Sheet Metal	3,990	24,360,217	1.84	-	10, 20
Wood	Small Dimension Lumber, Softwood Plywood, Large Dimension Lumber	12,494	9,658,520	0.54	-	10, 20
Gypsum Wall Board	Gypsum Wall 0.5” and 0.625”	496	1,800,000	0.12	-	5, 20
Vapour Barrier	6 mil Polyethylene, EPDM Membrane	247	108,000,000	3.35	-	5, 20
Insulation	Batt fibreglass, Brick, Vinyl Siding	29,290	12,535,586	0.67	-	10, 20
Glass	Glazing Panel, Low E Tin Argon Filled Glazing	42,000	15,000,000	0.85	-	10, 20
Other	Aluminum	367	28,800,000	1.69	-	5, 20

Because no information is available about transportation distances from producer to the site, assumptions are made as described in Table 5.3 . Mixed mode transport can be accommodated in a manner similar to the material quantities, namely, by using weighted averages of the modes of transportation by material quantity and distance. However, for the analysis, the mode of freight transport assumed is a diesel heavy truck from the producer to the site. The embodied energy database used for the values includes sourcing transportation, and is therefore not considered in the transportation distances here. The distances are assumed since no information is available from the original study. The distances are created in Rt using constant values and the transportation intensities are assigned lognormal distributions with a coefficient of variation of 10%. The intensity values are obtained from Table 4.7. The GWP intensity value is assigned a coefficient of variation of 20%.

Table 5.3 Assumed transportation distances

Rt Material Category	Mode of Transportation	Transportation Distance (km)	Transportation Energy Intensity (J/kg/km)	Transportation GWP Intensity (kgCO2e/kg/km)
Concrete	Diesel Heavy Truck	15	2400	0.00017
Steel		20		
Wood		15		
Gypsum Wall Board		15		
Vapour Barrier		20		
Insulation		20		
Glass		15		
Other		20		

For the on-site construction phase, there was no information available regarding the details, length of construction or construction crew. Therefore, reasonable assumptions were made regarding the likely scenario of construction. The typical construction of a wood-frame house takes 16 weeks (Burrows 2006). Assuming that work occurs five days of the week, and that there are 8 hours of work in every shift, there are a total of 640 hours. It is assumed that there are five workers, which yields 3,200 worker hours. Table 5.4 summarizes the assumed parameters used in Rt for this life cycle stage. The manual worker energy intensity has been assumed to be 0.75 MJ/worker hour to roughly represent an 800W gasoline powered generator running for every four workers. The energy intensity for heavy machinery is taken to be twice that of manual work, 1.5MJ/worker hour. There is a need for more research to verify these values as intensities are generally related to machinery rather than operation. The transportation values have been developed using Table 4.9 presented earlier for passenger transportation (assuming 30% automobile, 50% diesel truck, 20% trolley bus). According to Sharrard, gasoline and diesel fuel account for 62-75% of all energy use in construction (2007), hence the assumptions made here are considered reasonable approximations.

Table 5.4 Construction related inputs

Parameter	Distribution Type	Value / Mean	Coefficient of Variation
Total worker hours	Lognormal	3200	5%
Ratio of worker hours of heavy machinery to total	Constant	0.0625	-
Energy intensity of worker transportation (J/passenger/km)	Lognormal	1,360,000	5%
GWP intensity of worker transportation (kg CO_2e/passenger/km)	Lognormal	0.12	20%
Worker travel distance (km)	Constant	20	-
Heavy machinery energy intensity (J/worker-hour)	Lognormal	1,500,000	15%
Manual energy intensity (J/worker-hour)	Lognormal	750,000	15%
Heavy machinery GWP intensity (kg CO_2e/worker-hour)	Lognormal	0.318	20%
Manual GWP intensity (kg CO_2e /worker-hour)	Lognormal	0.106	20%
Water intensity (L/worker hour)	Lognormal	0.5	20%

Parameter	Distribution Type	Value / Mean	Coefficient of Variation
Transportation Water Intensity (L/km/passenger)	Constant	0	-

For energy use during operation, Zachariah reports the values presented in Table 5.5 from the HOT2000 software simulation. The total annual energy demand is used as input in the Rt model with a lognormal distribution and coefficient of variation of 5%.

Table 5.5 Annual energy demand breakdown

Energy Purpose	Annual Energy Demand (J)
Space Heating and Cooling	70,580,000,000
Domestic Hot Water Heating	26,598,000,000
Electric Ventilators	1,710,000,000
Electricity	34,690,000,000
Total	133,578,000,000

For water usage estimates, the following fixture types are obtained from the cost estimate in the original study: bathroom sink, shower, toilet and kitchen sink. Using the values presented in Table 4.20 and knowledge that the home serves four individuals estimates are made for the water demands during operation. The summary of the inputs used for the operation phase of the water model is provided in Table 5.6. The GWP intensity of the operation phase is determined from assuming that space heating and domestic hot water heating demands are met through the use of natural gas and the rest from electricity.

Table 5.6 Operation related inputs

Parameter	Distribution Type	Value / Mean	Coefficient of Variation
Annual energy (J)	Lognormal	133,578,000,000	5%
GWP intensity of operation energy (kg/J)	Lognormal	0.006	20%

Parameter	Distribution Type	Value / Mean	Coefficient of Variation
Days of yearly operation	Constant	365	-
Total building occupants	Constant	4	-
Flow fixture water demand (L/occupant/day)	Lognormal	52.25	10%
Flush demand males (L/female occupant/day)	Lognormal	11.4	10%
Flush demand females (L/male occupant/day	Lognormal	7.6	10%
Ratio male occupants	Constant	0.5	-
Design life (years)	Constant	35	-

The maintenance phase is ignored, as the design life is taken to be 35 years, and no replacement is expected to be necessary. Should the design life increase, materials with replacement lives shorter than the building should be allocated for replacement and intensities approximated in the model.

The end of life phase can be assumed to involve demolition, deconstruction and recovery of metal materials for up-cycling. There are several approaches taken in the literature, the most common being a landfill option. Other possibilities are to take the up-cycling of material as a credit for an avoided process, such as the extraction of virgin materials. This is a point of controversy that deserves further debate as some materials are well established for up-cycling, such as steel, and it appears excessive to grant a credit for the avoided extraction of raw material. Thus, for this example, the only burden at the end of life is for dismantling, while sorting and transporting the material to recycling facilities or for reuse is viewed as a burden for the life cycle of the future building. It is assumed that the intensity of demolition is 1,000 J/kg of material, modeled as a lognormal distribution with a coefficient of variation of 25%.

The total life cycle estimate is then computed by introducing all relevant variables into the Rt implementation of the fine detail models proposed. The next chapter presents the results obtained.

5.3 Results

This section presents the results obtained from the application of the fine-detail models to the example residence. Figure 5.1 provides a histogram of the life cycle energy as reported by Rt after 1,000,000 Monte Carlo samples. When establishing a limit state function to calculate the probability of exceedance of 6.5 TJ using the First Order Reliability Method capabilities within Rt, a value of 0.05 is obtained. This means that given the inputs, there is a 5% probability that the life cycle energy of 6.5 TJ will be exceeded. Table 5.7 lists the gamma importance measures from the random variable inputs. These indicate that the annual energy use, as well as the energy intensity of materials, influences the results significantly. Designers can use this information to direct their efforts to reduce environmental impact.

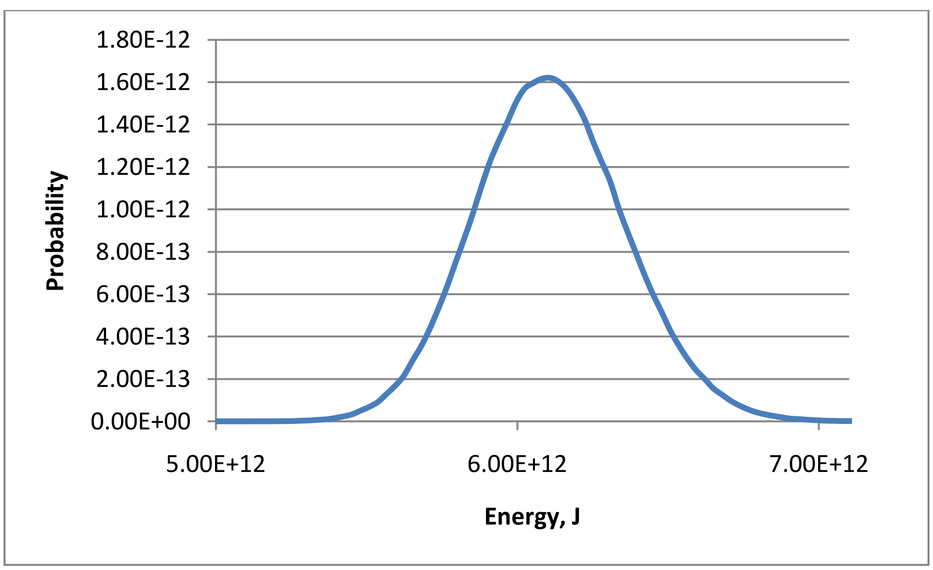

Figure 5.1 Life cycle energy usage for example residence

Table 5.7 Gamma importance measures

Random Variable	Gamma Importance Measure
Annual Energy	0.96
Energy Intensity of Glass	0.25
Energy Intensity of Insulation	0.14
Energy Intensity of Wood	0.05
Energy Intensity of Steel	0.04
Energy Intensity of Concrete	0.02
Energy Intensity of Worker Travel	0.01
Energy Intensity of Vapour Barrier	$5.0 \cdot 10^{-3}$
Energy Intensity of Heavy Diesel Truck	$2.9 \cdot 10^{-3}$
Total Worker Hours	$2.2 \cdot 10^{-3}$
Energy Intensity of Aluminum	$2.0 \cdot 10^{-3}$
Manual Energy Intensity	$1.2 \cdot 10^{-3}$
Energy Intensity of Gypsum Wall Board	$1.7 \cdot 10^{-4}$
Heavy Machinery Energy Intensity	$1.7 \cdot 10^{-4}$
Energy Intensity of End of Life	$1.1 \cdot 10^{-8}$

The life cycle energy usage for the example residence in Ontario was estimated at 6.1 TJ by using the mean value of all the random variables. Normalized according to floor area this is 21.7 GJ/m^2. Additionally, normalized to building occupants, this translates to 1.52 TJ/occupant for the life cycle of the residence.

The life cycle water was then computed. Figure 5.2 provides a histogram of the life cycle water usage as reported by Rt after 1,000,000 random realizations. As noted earlier, the water estimate does not consider embodied water impacts since water intensity factors for materials were not found. Further research is necessary in this respect.

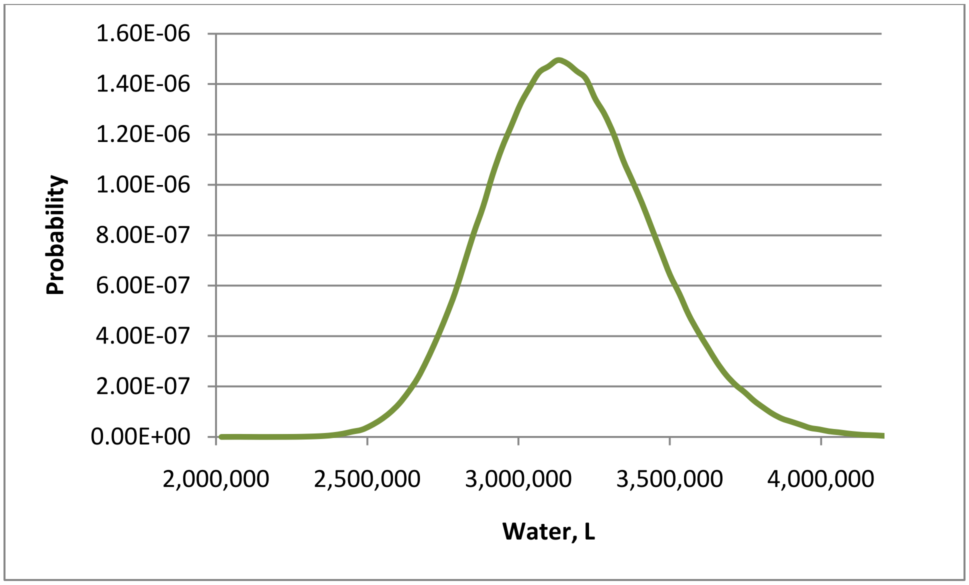

Figure 5.2 Life cycle water usage for example residence

The life cycle water usage was estimated at 3.157×10^6 L of water by evaluating at the mean of the random variables. Normalized according to floor area this is 11,275 L/m^2. Additionally, normalized to building occupants, this translates to 789,250 L/occupant for the life cycle of the residence.

The last environmental impact to be estimated was GWP. Figure 5.3 provides a histogram of the life cycle water usage as reported by Rt after 1,000,000 random realizations. As noted earlier, the water estimate does not consider embodied water impacts since water intensity factors for materials were not found. Further research is necessary in this respect.

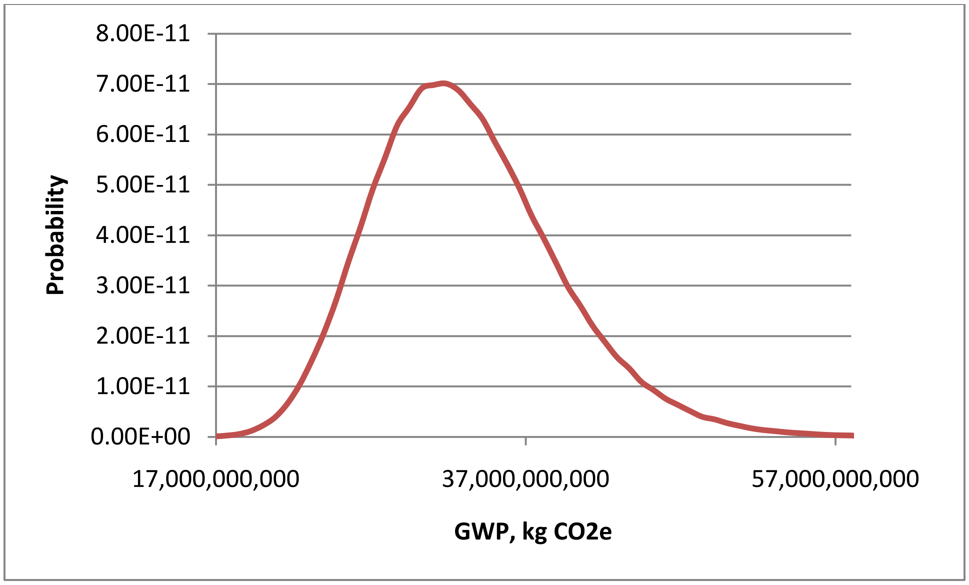

Figure 5.3 Life cycle GWP for example residence

The life cycle GWP generation was estimated at 3.248×10^{10} kg of CO_2e by evaluating the life cycle GWP expression at the mean of the random variables. Normalized according to floor area this is kg of 1.16011×10^{8} CO_2e/m^2. Additionally, normalized to building occupants, this translates to 8.12078×10^{9} kg of CO_2e/occupant for the life cycle of the residence.

As mentioned earlier, the maintenance phase was omitted in all models since most of the materials included in the analysis were not expected to require replacement through the design life of 35 years. Table 5.8 reports the values obtained from the sampling analysis of the life cycle energy usage, water usage, and GWP generation for the example residence.

Table 5.8 Summary results table

Life Cycle Impact	Mean	Standard Deviation	Coefficient of Variation (%)
Energy (J)	$6.11\cdot10^{12}$	$2.46\cdot10^{11}$	4
Water (L)	$3.17\cdot10^{6}$	$2.71\cdot10^{5}$	8.5
GWP (kg CO_2e)	$3.32\cdot10^{10}$	$5.98\cdot10^{9}$	18

The results identify a significant use of energy and water resources as well as the generation of a significant amount of greenhouse gases. Importantly, it is shown that calculated values have significant variability. This is a feature that is not available when performing deterministic analysis with other software tools like Athena's Impact Estimator.

It is reemphasized that it remains difficult to obtain information on the extraction and manufacture intensities of building materials. In the example provided, a public document that reports such values for energy and greenhouse gas emissions is utilized. Assumptions are made on the statistical representation of such values. Unfortunately, intensity values for water are not readily available for building materials. Additional intensity values are used for transportation, on-site construction and end of life intensities. In the example, the simplification of neglecting building material replacement was possible due to the design life of 35 years. This was convenient since in general replacement frequency data is scarce. Such data is expected to vary widely among buildings that serve different functions. Overall, it is recognized that more detailed studies are needed to properly understand the intricacies of the building stock, particularly for the purpose of modeling. The proposed framework is particularly useful for being able to accommodate data that are uncertain. Consequently, the results are more informative.

In the histograms above it is evident that the environmental impact estimates could easily exceed or be underestimated by the mean values. The example provided with the life cycle energy, where the probability of exceeding 6.5 TJ is calculated using reliability methods is a unique and distinctive feature of the methodology and its implementation in Rt. Additionally, several building design options could be explored with the aim of selecting the one that produces the smallest and least variable life cycle impacts or identifying the variables that are most influential in each impact (through means of importance vectors).

The development of intensity values has been proposed as a way of helping designers become more familiar with the traditional "black box" approaches to relate impacts to quantities of materials or distances travelled. By revealing these values in a transparent manner, we can expose them to further scrutiny to discuss how valid they are and how to best approximate them. While tedious, the development of these intensity values on a regional basis is a one-time expense. Later on, these random variable intensities can be loaded into software like Rt and material quantities can be queried from a Building Information Model to reduce the need to manually input all the necessary information. Additionally, the intensity approach offers greater flexibility to incorporate new technologies and materials, being able to subjectively assign higher coefficients of variation to "riskier" technologies and analyze results in a computationally fast manner.

Overall, the methodology presented has significant potential to better estimate environmental impacts of buildings and other infrastructure in a way that informs decision-making. A simple residential example in Canada has been analyzed and the results presented. The implementation allows designers to incorporate uncertainty and perform analyses in a time effective and computationally feasible manner. Further work and refinement of the proposed models is encouraged to reduce the model uncertainty in the estimates of environmental impacts of buildings.

6 Conclusion

The life cycle study of buildings and other infrastructure is a challenging undertaking that requires large amounts of data from various disciplines and sources. A probabilistic framework of environmental impact models has been proposed in this thesis. This section offers a summary of the work performed and recommendations for future research.

6.1 Summary

This thesis began by introducing different tools to estimate the environmental impact of buildings and reviewing how previous studies have approached this problem. An alternate probabilistic methodology was then presented which includes explicit mathematical models for estimating energy, GWP and water demands over a building's life cycle at different levels of data refinement. The methodology is heavily reliant on the idea of developing intensity factors that relate environmental impact to different explanatory variables and presents an effort at a predictive, rather than relative analysis approach. Finally, the models are implemented in the Rt software application and results were obtained for an example residence in Ontario. The implementation demonstrates a high degree of transparency in calculating the life cycle impacts of buildings. Through the example study, it was found that better databases are required to document the environmental impact intensities of building materials, particularly those that relates to water demand.

Although tedious to develop, the intensity approach used allows greater flexibility and understanding of what influences the environmental impacts of buildings and is better able to incorporate emerging materials. Use of such intensities should also stimulate a necessary discussion on what values are reasonable for building materials and other life cycle phases. The research effort has attempted to fill the gap identified by Sanchez-Silva and Rosowsky (2008), in quantifying environmental impacts in the built environment.

The present work has attempted to advance knowledge by proposing a framework that is universally applicable to most buildings. The presented models are particularly innovative on the grounds that they incorporate uncertainty in the form of random variables that can be assigned a variety of statistical distributions. The use of reliability methods to investigate the probabilities of exceeding a life cycle impact value enters well-established decision approaches in the field of structural safety. In fact, the use of reliability methods could be adopted as a way of introducing cost-benefit-balanced policy for building design, including life cycle energy values determined by building type and size. Nonetheless, the present study has revealed some gaps in understanding remain which should be addressed by future research.

6.2 Future Research

Several future research objectives have been identified throughout this document. Items requiring future attention are summarized in this section. As an overall comment on future work, it is also noted that an important objective in this thesis was to establish a generic framework of models that promotes and facilitates a continuous improvement of these models.

Recommended future refinements include developing a quantification of “softer” issues that are relevant in building construction such as: appropriate levels of day lighting, construction and maintenance, vibrations, sound transmission within the building, indoor air quality and comfort. Even very detailed models of environmental impacts may lead to optimal solutions that are not amenable for building occupants and may give rise to user complaints. In low energy buildings, there is increasing concern with sound transmission and air quality due to the use of natural ventilation strategies.

More interdisciplinary work is necessary to model the complexity and interactions of real life. It is impractical to investigate sustainability in the isolation of a single discipline, much less to build the expertise necessary to integrate the various models available within the entire academic domain. An interdisciplinary approach may lead to more robust predictive models such as those that relate to energy or water usage during operation by taking realistic and uncertain behaviour patterns into account.

In quantifying impacts using coarse data, it is important to estimate the quantities of materials present in a building. Future research should attempt to develop models based on structural system and floor area that can quantify more accurately the materials necessary in traditional construction in order to properly characterize their actual variability. This would improve the application of the coarse models developed in this thesis.

Quantifying social indicators is an important step that is in tune with the concept of sustainability. Some decisions like local vs. overseas sourcing may not have significant energy or GWP effects, but local sourcing may provide important socio-economic benefits that deserve attention. An investigation of relevant indicators in that respect is needed.

The evaluation of cost is important, as designers are likely to support environmentally conscious decisions as long as they are able to meet their budget. For that reason, coupling environmental data and costs is an important next step to make the methodology presented most useful.

The application and extension of the current methodology should be applied to regional studies. This will require the quantification of the environmental impact of roads, paved surfaces, pipe networks and bridges. A discussion of what time frames of analyses are relevant at this scale should begin taking place.

The methodology should be integrated with existing building information modeling software. The automation of the extraction of quantity information from a 3-D building model can make the proposed methodology more amenable to structural engineers and architects. This extension would also provide an opportunity to develop more powerful design support tools to visualize results. For example, a useful feature could be to visually color code which building components contribute different degrees of environmental impact to a particular stage of the building's life cycle.

Additionally, the idea has been presented to normalize environmental impacts to building occupants rather than to floor area. As the area of the built environment grows, care must be taken so that energy efficiency gains are not lost with the erection of larger buildings that as a whole consume more energy and resources. The life cycle methodology presented is a partial step in this direction by proposing to normalize to building occupants in addition to floor area.

Even with the growing number of studies that concern the environmental impact of buildings, there is still very limited research about the on-site construction, maintenance and end of life stages of buildings. What little information is known has been limited to particular building types such as offices. Thus, a better and more general understanding of the entire building stock is urgently required to refine current models. On a similar note, actions like the one taken by the City of Vancouver (City of Vancouver 2010b), to make data on the built environment publicly available online, is a great way to encourage researchers to better investigate and understand buildings and infrastructure.

Finally, the proposed framework has the ability to expand in the future to include the impact that hazards have on environmental life cycle impact results. Since hazards create significant amounts of damage, they prompt the replacement of many building materials. There is a potentially high environmental cost associated with these events. This is a research gap that could highlight the role and importance of structural engineers in sustainability assessments.

References

Adalberth, K. (1997a). "Energy use during the life cycle of buildings: a method." *Build.Environ.*, 32(4), 317-320.

Adalberth, K. (1997b). "Energy use during the life cycle of single-unit dwellings: Examples." *Build.Environ.*, 32(4), 321-329.

Alberti, M. (1996). "Measuring urban sustainability." *Environmental Impact Assessment Review*, 16(4-6), 381-424.

Athena Institute. (2010a). "The Athena Institute - Impact Estimator - Companion LCI Database Reports." http://www.athenasmi.org/tools/impactEstimator/companionLCIDatabaseReports.html (Jun. 20, 2010).

Athena Institute. (2010b). "EcoCalculator." http://www.athenasmi.org/tools/ecoCalculator/ (Sept. 20, 2010).

Athena Institute. (2004). "Minnesota Demolition Survey: Phase Two Report." http://www.athenasmi.ca/about/docs/Demolition_Survey.pdf (Jan. 12, 2010).

Autodesk. (2010). "Autodesk Green Building Studio." http://www.autodesk.com/greenbuildingstudio (Aug. 20, 2010).

Bare, J. C., Norris, G. A., Pennington, D. W., and McKone, T. (2002). "TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts." *J.Ind.Ecol.*, 6 49-78.

Blengini, G. A. (2009). "Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy." *Build.Environ.*, 44(2), 319-330.

Blengini, G. A., and Di Carlo, T. (2010). "The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings." *Energy Build.*, 42(6), 869-880.

Box, G. E. P., and Tiao, G. C. (1973). *Bayesian inference in statistical analysis.* Addison-Wesley Pub. Co., Reading, MA.

British Columbia Government. (2009). "CAS - B.C. GHG Inventory Report." http://www.env.gov.bc.ca/cas/mitigation/ghg_inventory/ (Jun. 20, 2010).

Brown, Z., and Cole, R. J. (2009). "Influence of occupants' knowledge on comfort expectations and behaviour." *Build.Res.Inf.*, 37(3), 227.

Brunklaus, B., Thormark, C., and Baumann, H. (2010). "Illustrating limitations of energy studies of buildings with LCA and actor analysis." *Building Research and Information*, 38(3), 265-279.

Building Research Establishment. (2009). "BREEAM: News." http://www.breeam.org/newsdetails.jsp?id=542 (Mar. 9, 2009).

Burrows, J. (2006). *Canadian wood-frame house construction.* Canada Mortgage and Housing Corporation, Ottawa.

Canada Green Building Council. (2004). *LEED v.1.0 Green Building Rating System for New Construction & Major Renovations.* CaGBC, Vancouver.

Canadian Standards Association. (2006a). *CAN/CSA-ISO 14040:06 Environmental management : life cycle assessment : principles and framework.* Canadian Standards Association, Mississauga, Ont.

Canadian Standards Association. (2006b). *CAN/CSA-ISO 14044:06 Environmental management : life cycle assessment : requirements and guidelines = Management environnemental : analyse du cycle de vie : exigences et lignes directrices.* Canadian Standards Association, Mississauga, Ont.

Canadian Standards Association. (2006c). *Guideline for design for disassembly and adaptability in buildings.* Canadian Standards Association, Mississauga, ON.

CEC. (2008). *Green building in North America opportunities and challenges: Secretariat report to Council under Article 13 of the North American Agreement on Environmental Cooperation.* Commission for Environmental Cooperation, Montréal, Québec.

Center for Resilience. "Resiliency and Sustainability Tools." http://www.resilience.osu.edu/CFR-site/eco-lca.htm (Nov. 18, 2009).

Centre for Interactive Research on Sustainability. (2008). "What is Sustainability?" http://www.cirs.ubc.ca/about/sustainability.php (Aug. 27, 2010).

Cheng, C. (2002). "Study of the inter-relationship between water use and energy conservation for a building." *Energy Build.*, 34(3), 261-266.

City of Vancouver. (2010a). "Media Room - News Releases." http://vancouver.ca/mediaroom/news/detail.htm?row=109&date=2010-07-22 (Aug. 25, 2010).

City of Vancouver. (2010b). "Vancouver's Open Data Catalogue." http://data.vancouver.ca/ (Jun. 11, 2010).

Cleveland, A. (1988). *Means man-hour standards for construction.* R.S. Means Co., Kingston, MA.

Cole, R. J. (1998). "Energy and greenhouse gas emissions associated with the construction of alternative structural systems." *Build.Environ.*, 34(3), 335-348.

Cole, R. J., and Kernan, P. C. (1996). "Life-cycle energy use in office buildings." *Build.Environ.*, 31(4), 307-317.

Costanza, R., Cumberland, J. H., Daly, H. E., Goodland, R., Norgaard, R. L., and Economics, I. S. f. E. (1997a). *An Introduction to Ecological Economics.* Saint Lucie Press, Boca Raton, Florida.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., and van, d. B. (1997b). "The value of the world's ecosystem services and natural capital." *Nature,* 387(6630), 253-260.

Cuddihy, J., Kennedy, C., and Byer, P. (2005). "Energy use in Canada: environmental impacts and opportunities in relationship to infrastructure systems." *Canadian Journal of Civil Engineering,* 32(1), 1.

Daly, H. E. (1991). *Steady-state economics.* Island Press, Washington, D.C.

Darwin, C. (1958). *The Autobiography of Charles Darwin, and selected letters.* Dover Publications, New York.

Domínguez-Muñoz, F., Cejudo-López, J. M., and Carrillo-Andrés, A. (2010). "Uncertainty in peak cooling load calculations." *Energy Build.,* 42(7), 1010-1018.

Dong, B., Kennedy, C., and Pressnail, K. (2005). "Comparing life cycle implications of building retrofit and replacement options." *Canadian Journal of Civil Engineering,* 32(6), 1051.

Elkington, J. (1998). *Cannibals with forks: the triple bottom line of 21st century business.* Gabriola Island, BC ; New Society Publishers, c1998., .

Farber, S. C., Costanza, R., and Wilson, M. A. (2002). "Economic and ecological concepts for valuing ecosystem services." *Ecol.Econ.,* 41(3), 375-392.

Filion, Y. R. (2008). "Impact of Urban Form on Energy Use in Water Distribution Systems." *J Infrastruct Syst,* 14(4), 337-346.

George, C. (1999). "Testing for sustainable development through environmental assessment." *Environ.Impact Assess.Rev.,* 19(2), 175-200.

R. Gibson. (2001). "Specification of sustainability-based environmental assessment decision criteria and implications for determining "significance" in environmental assessment." http://static.twoday.net/NE1BOKU0607/files/Gibson_Sustainability-EA.pdf (Apr. 28, 2009).

Gorgolewski, M. (2006). "The implications of reuse and recycling for the design of steel buildings." *Canadian Journal of Civil Engineering,* 33(4), 489-496.

Graedel, T. E., and Allenby, B. R. (2009). *Industrial Ecology and Sustainable Engineering.* Prentice Hall, NJ.

Green Design Institute at Carnegie Mellon. (2010). "Economic Input-Output Life Cycle Assessment - Carnegie Mellon University." http://www.eiolca.net/ (Feb. 17, 2010).

Green Globes. (2010). "Building Environmental Assessments - Welcome." http://www.greenglobes.com/ (Feb. 27, 2010).

Groß, J. (2003). *Linear Regression (Lecture Notes in Statistics).* Springer, New York.

Guggemos, A. A., and Horvath, A. (2005). "Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings." *J Infrastruct Syst*, 11(2), 93-101.

Gustavsson, L., Joelsson, A., and Sathre, R. (2010). "Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building." *Energy Build.*, 42(2), 230-242.

G. Hammond, and Jones, C. (2008). "Inventory of carbon & energy ICE." http://www.bath.ac.uk/mech-eng/sert/embodied/ (Jun. 1, 2010).

Haukaas, T. (2008). "Unified reliability and design optimization for earthquake engineering." *Prob.Eng.Mech.*, 23(4), 471-481.

Haukaas, T., and Bohl, A. (2009). "Comparison of Approaches for Performance-Based Earthquake Engineering." *Earthquake Engineering by the Beach Workshop*, Capri, Italy, 1-12.

Hecht, J. E. (2005). *National environmental accounting : bridging the gap between ecology and economy.* Resources for the Future, Washington, DC.

Hendrickson, C., and Lave, L. B. (2006). *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach.* RFF Press, Washington, DC.

Hernandez, P., and Kenny, P. (2010). "From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)." *Energy Build.*, 42(6), 815-821.

Huijbregts, M. (1998). "Application of uncertainty and variability in LCA." *The International Journal of Life Cycle Assessment*, 3(5), 273-280.

International Code Council. (2010). "ICC Sustainable Building Technology Committee (SBTC)." http://www.iccsafe.org/cs/SBTC/Pages/default.aspx (Feb. 17, 2010).

International Living Building Institute. (2010). "The International Living Building Institute issues a challenge: — ILBI." http://ilbi.org/the-standard/ (Feb. 16, 2010).

IPCC. (2010). "IPCC - Intergovernmental Panel on Climate Change." http://www.ipcc.ch/ (Sept. 18, 2010).

Jonsson, A., Bjorklund, T., and Tillman, A. (1998). "LCA of concrete and steel building frames." *The International Journal of Life Cycle Assessment*, 3(4), 216-224.

Junnila, S., and Horvath, A. (2003). "Life-Cycle Environmental Effects of an Office Building." *J Infrastruct Syst*, 9(4), 157-166.

Keoleian, G., and Spitzley, D. (2006). "Life Cycle Based Sustainability Metrics." *Sustainability science and engineering: defining principles,* M. A. Abraham, ed., Elsevier, Amsterdam, 127-158.

Kibert, C. J. (2008). *Sustainable construction : green building design and delivery.* John Wiley & Sons, Hoboken, N.J.

Leontief, W. (1970). "Environmental Repercussions and the Economic Structure: An Input-Output Approach." *Rev.Econ.Stat.,* 52(3), 262-271.

Levasseur, A., Lesage, P., Margni, M., DescheÌ,nes, L., and Samson, R. (2010). "Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments." *Environ.Sci.Technol.,* 44(8), 3169-3174.

Liang, H., Haukaas, T., and Royset, J. O. (2007). "Reliability-based optimal design software for earthquake engineering applications." *Canadian Journal of Civil Engineering,* 34(7), 856-869.

MacKay, D. J. C. (2009). *Sustainable energy without the hot air.* UIT Cambridge, Cambridge, England.

M. Mahsuli, and Haukaas, T. (2009). "Rt: Reliability tools." http://www.inrisk.ubc.ca/software.htm (Mar. 8, 2010).

McDonough, W., and Braungart, M. (2002). *Cradle to cradle : remaking the way we make things.* North Point Press, New York.

National Institute of Standards and Technology. (8/20/2007). "BEES 4.0: BFRL Office of Applied Economics." http://www.bfrl.nist.gov/oae/software/bees/bees.html (Feb. 24, 2010).

Natural Resources Canada. (2010). "Transportation Sector – Energy Use Analysis." http://www.oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablesanalysis2/tran_00_1_e_4.cfm?attr=0 (Aug. 30, 2010).

Natural Resources Canada. (2009). "Energy Efficiency in Buildings, Homes and Communities | Natural Resources Canada's CanmetENERGY | Leadership in ecoInnovation." http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/buildings_communities.html (Mar. 4, 2010).

Norman, W., and MacDonald, C. (2004). "Getting to the Bottom of "Triple Bottom Line"." *Business Ethics Quarterly*, 14(2), 243-262.

Norris, G. A. (2002). "Impact Characterization in the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts." *J.Ind.Ecol.,* 6(3-4), 79.

Norris, G. (2001). "Integrating life cycle cost analysis and LCA." *The International Journal of Life Cycle Assessment,* 6(2), 118-120.

J. O'Connor, and Dangerfield, J. (2004). "The Environmental Benefits of Wood Construction." http://www.ewpa.com/Archive/2004/jun/Paper_030.pdf (Sep. 20, 2010).

Optis, M., and Wild, P. (2010). "Inadequate documentation in published life cycle energy reports on buildings." *The International Journal of Life Cycle Assessment,* 15(7), 644-651.

PE International. (2010). "GaBi Software: Building LCA." http://www.gabi-software.com/solutions/building-lca/ (Aug. 12, 2010).

Pérez-Lombard, L., Ortiz, J., and Pout, C. (2008). "A review on buildings energy consumption information." *Energy Build.,* 40(3), 394-398.

Polak, E. (1971). *Computational methods in optimization; a unified approach.* Academic Press, New York,.

Poudenx, P., and Merida, W. (2007). "Energy demand and greenhouse gas emissions from urban passenger transportation versus availability of renewable energy: The example of the Canadian Lower Fraser Valley." *Energy,* 32(1), 1-9.

Ramesh, T., Prakash, R., and Shukla, K. K. (2010). "Life cycle energy analysis of buildings: an overview." *Energy Build.,* In Press, Accepted Manuscript.

Rao, C. N. R., and Toutenburg, H. (1999). *Linear models: least squares and alternatives.* Springer, New York.

Rees, W. (2003). "Understanding Urban Ecosystems: An Ecological Economics Perspective." *Understanding Urban Ecosystems,* K. Hollweg, A. Berkowitz, and C. Nilon, eds., Springer, New York, 115-135.

G. Reyallo. (2010). "Chile Earthquake Assessment Report." http://www.reliefweb.int/rw/RWFiles2010.nsf/FilesByRWDocUnidFilename/VDUX-83FTPM-full_report.pdf/$File/full_report.pdf (May 3, 2010).

Robèrt, K. (2000). "Tools and concepts for sustainable development, how do they relate to a general framework for sustainable development, and to each other?" *Journal of Cleaner Production,* 8(3), 243-254.

Ross, S., Evans, D., and Webber, M. (2002). "How LCA studies deal with uncertainty." *The International Journal of Life Cycle Assessment,* 7(1), 47-52.

Sanchez-Silva, M., and Rosowsky, D. V. (2008). "Risk, reliability and sustainability in the developing world." *Proceedings of the Institution of Civil Engineers: Structures and Buildings,* 161(4), 189-197.

Sanchez-Silva, M., and Rackwitz, R. (2004). "Socioeconomic Implications of Life Quality Index in Design of Optimum Structures to Withstand Earthquakes." *J.Struct.Engrg.,* 130(6), 969-977.

Sassi, P. (2008). "Defining closed-loop material cycle construction." *Building Research &; Information,* 36(5), 509-519.

Scheuer, C., Keoleian, G. A., and Reppe, P. (2003). "Life cycle energy and environmental performance of a new university building: modeling challenges and design implications." *Energy and Buildings,* 35(10), 1049-1064.

Scott, D. S. (1993). "Hydrogen in the evolving energy system." *Int J Hydrogen Energy*, 18(3), 197-204.

Sharrard, A. L. (2007). "Greening construction processes using an input-output-based hybrid life cycle assessment method." PhD thesis, Carnegie Mellon University, United States -- Pennsylvania.

Suh, S., and Huppes, G. (2005). "Methods for Life Cycle Inventory of a product." *J.Clean.Prod.,* 13(7), 687-697.

Thormark, C. (2006). "The effect of material choice on the total energy need and recycling potential of a building." *Build.Environ.,* 41(8), 1019-1026.

Toffoletto, L., Bulle, C., Godin, J., Reid, C., and Deschenes, L. (2007). "LUCAS - A New LCIA Method Used for a Canadian-Specific Context." *The International Journal of Life Cycle Assessment*, 12(2), 93-102.

U.S. Department of Energy. (2010). "Building Technologies Program: EnergyPlus Energy Simulation Software." http://apps1.eere.energy.gov/buildings/energyplus/ (Sep. 20, 2010).

United Nations Conference on Environment and Development. (1993). "Agenda 21 : programme of action for sustainable development ; Rio Declaration on Environment and Development ; Statement of forest principles." United Nations, New York, NY, .

United Nations Environment Programme, and Regional Resource Centre for Asia and the Pacific. (2004). *Environmental indicators, South Asia.* United Nations Environment Programme, Regional Resource Centre for Asia and the Pacific, Pathumthani, Thailand.

US Green Building Council. (2010). "USGBC: About USGBC." http://www.usgbc.org/About (Oct. 16, 2010).

US Green Building Council. "USGBC: U.S. Green Building Council." http://www.usgbc.org/ (Nov. 16, 2008).

Van Nederveen, S., and Gielingh, W. (2009). "Modelling the life-cycle of sustainable, living buildings." *Electron.J.Inf.Technol.Constr.*, 14 674-691.

World Commission on Environment and Development. (1987). *Our common future.* Oxford University Press, Oxford; New York.

Yudelson, J. (2009). *Green building through integrated design.* New York : McGraw-Hill, c2009., .

Zabalza Bribián, I., Aranda Usón, A., and Scarpellini, S. (2009). "Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification." *Build.Environ.*, 44(12), 2510-2520.

Zachariah, J. L. (2003). "Towards sustainable homes through optimization: An approach to balancing life cycle environmental impacts and life cycle costs in residential buildings." PhD thesis, University of Toronto, Canada.