APPLICATION OF LIFE-CYCLE APPROACHES FOR THE EVALUATION OF HIGH PERFORMANCE BUILDINGS

by

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M.A.Sc., The University of British Columbia, 2007

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE AND POST DOCTORAL STUDIES

(Resource Management and Environmental Studies)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2014

Abstract

The market shift towards high performance buildings is posing a major challenge to decision-makers, designers and developers. They need to know what constitutes high performance design and practice, what the environmental consequences of decisions are, and how buildings are performing relative to anchored benchmarks. This doctoral dissertation provides building designers and operators methods on how to use life-cycle approaches to inform design and track performance. The research focuses on a case-study of the lifecycle impacts of advanced buildings at UBC, built to various standards of performance including the current best-practices (LEED standards) and the currently emerging 'regenerative' standard. Life-cycle approaches are used to explore simulated impact over time in terms of quantified financial and environmental metrics. The research novelty is in the integration of life-cycle models; the aggregation of compatible separate studies to provide a larger overview of building performance. Additionally, the analysis leverages the benchmarking capabilities of the UBC Life-cycle Analysis database - a high-resolution survey of 30 UBC buildings – to show that the contribution of rapid churn building products, such as information technology, contributes a disproportionally high amount to embodied impacts. The study also analyses operational impacts based on utility consumption data for 70 conventional buildings versus 10 best practices (LEED Gold) buildings at UBC with respect to building age and building type. The results show that, in contrast to previous studies, older buildings often outperform new buildings. The dissertation concludes that benchmarking and multi-stakeholder modeling life-cycle approaches are critical for informing expert opinion during decision-making. Attention to modeling construction, and ensuring broad

participation is key to ‘useful’ modeling. The process of creating a life-cycle model is often more informative than modeled final results; collective understanding and communication – the basis of good decision-making – improve through participation and stakeholder interaction.

Preface

Chapters 2-4 of this dissertation have been developed to form future manuscripts for publication in peer-reviewed journals. All of the chapters have been peer reviewed by collaborators; Chapters 2, 3, and 4 have received various types of research partner contributions via data provision, as discussed below.

Chapter 1 uses content generated by the author in previous work. This includes content written for comprehensive examination, and script writings from at least 15 presentations delivered for conferences and industrial partners. Additionally, the chapter utilizes multi-criteria decision analysis content on the use of life-cycle approaches for decision-making taken from an interim report for the International Institute of Applied Systems Analysis written from June to August, 2010 (Storey 2010). The content for this chapter is entirely the work of the author including all tables, figures, and explanatory notes. Additionally, all associated appendices for this chapter are entirely the work of the author.

Chapter 2 has been written with input from John Metras, UBC Infrastructure development, Alberto Cayuela, UBC University Sustainability Initiative (USI) and John Robinson, UBC Associate Provost, Sustainability. Data support was obtained from UBC Properties Trust. Mentorship for the project was also received from Professor Mark Monroe, UBC Sauder School. The life-cycle costing tool, constructed in Excel, was 95% contributed by the author. Alberto Cayuela provided the remaining 5% as part of an original prototype tool. The Excel model contains other data worksheets, from research partners, that plug into the core model.

The worksheets were contributed from UBC Infrastructure Development (and includes Corix tendering data which provided the potential cost of operating green technologies.) The first cost benchmark model was 100% contributed by the author and contains public data from Board of Governors reports. Discount and escalation rates are data the Ministry of Advanced Education and from Stats Canada. All figures, tables, results and model outputs are 100% the work of the author, as are associated Appendices.

Chapter 3 has been written with the input of Rob Sianchuk, a UBC Instructor and co-director of Coldstream Consulting. The study utilizes the UBC-LCA database, an unpublished collection of whole-building life-cycle analysis (LCA) reports. The reports were developed over the period of 2009-2013 in a Civil Engineering course, CVL 498C, and represent the work of at least 60 students. The reports have been supervised and reviewed by Rob Sianchuk, who is the course author and instructor. Additional input has been provided by Max Richter of Perkins + Will Architects for the CIRS LCA analysis. The core, integrated model is a 100% contribution by the author, whereas the sub-modules have a variety of external contributions. The FF&E LCIA data was generated by Haworth but all modeling, including the analysis of the effect of churn rates (based on IEA and Athena estimates), was conducted by the author. The churn model was third party reviewed by Steve Kooy and his colleagues at Haworth. Haworth documentation was used to provide an explanation of the LCA methods and PCR standards used in modeling work. Rob Sianchuk generated the LCIA data for the construction models (both AERL and CIRS). The author later reviewed and revised the CIRS data by comparing the Athena results to a Bill of Materials, as generated by a 3D CIRS Revit model. The author is 100% responsible for Appendix sections B.1 to B.3.

Sianchuk is 95% responsible for the UBC-LCA data-base, including a 90% contribution to Appendix B.5 and the management of the UBC-LCA database. Teehan and the author jointly developed the ICT model. The contribution by Teehan is about 60% of the original model but the application of the data within the integrated model is entirely attributable to the author, as are all tables, figures, and analysis outputs..

Chapter 4 has been written with assistance from the Campus Sustainability Office (CSO). CSO provided data, via access to Pulse Energy and Ion meters, for operational consumption of UBC buildings. Energy data has been pre-processed by UBC Operations which constitutes a substantial input. Campus data was obtained from UBC Campus and Community Planning public documents. Review has been provided by co-author Lillian Zaremba (CSO). Rob Sianchuk provided the LCIA data for CIRS. Max Richter at Perkins and Will Architects supplied peer review. Sianchuk provided the original idea of figure 4.2 insofar as he identified that concrete was the primary cause of embodied GWP. The rest of the chapter, including model construction, was entirely the work of the author, as are all other figures, tables and findings. Similarly, all Appendices are the work of the author.

Table of contents

List of tables

List of figures

List of abbreviations

AIA – American Institute of Architects

ASHRAE – American Society of Heating, Refrigerating and Air Conditioning Engineers.

BAS – Building automation system

BEA – Building environmental assessment

BIM – Building information modeling

BMS – Building Management System

CIRS – Center for Interactive Research in Sustainability

FEMP – Federal Energy Management Program

ICT – Information and Computing Technologies

IDP – Integrated design process

IPD – Integrated product delivery

ISO – International Standards Organization

LCA – Life-cycle Analysis

LCC – Life-cycle Costing

LEED – Leadership in Energy and Environmental Design

MCDA – Multi Criteria Decision Analysis

NIST – National Institute of Standards and Technoology

OMB – Office of Management and Budget

POE – Post Occupancy Evaluation

USGBC – United States Green Building Council

Acknowledgements

The work contained in this dissertation would not have been possible without the help of many colleagues, nor would have been possible without the support of my research partners and funders.

First and foremost, I wish to convey my sincere thanks to my supervisor, Professor John Robinson, for his mentorship throughout my degree. John has been an inexhaustible source of ideas, inspiration and encouragement, and has helped me expand my educational horizon far beyond my expectations. To my colleagues, of which there are simply too many to list here, I am sincerely grateful for your help and support. I would also like to thank my research partners for their help over the years. This includes Perkins and Will Architects, Stantec Engineering, BC Hydro and Haworth Inc, all of which have provided data and expertise. I would like to thank my committee for their insight and support in structuring and navigating a path throughout my research work. Finally, this acknowledgement would be incomplete without thanking my family for their patience, support and encouragement.

This research was made possible by the Natural Sciences and Engineering Research Council of Canada (NSERC), a Doctoral Fellowship from the University of British Columbia, and by the generous support of BC Hydro.

Chapter 1: Introduction

Buildings contribute significantly towards the total environmental burden of energy and material consumption. The International Energy Agency (IEA) reports that 40% of primary energy use is attributable to building consumption (Dasgupta 2008; IEA 2008). With building standards and practices becoming increasingly stringent, building designers, owners and operators need access to a broad array of assessment methods and tools to help guide them through the process of designing a new building, refurbishing, or making informed operational decisions during the lifetime of a building (USGBC 2008; UNEP 2007; OECD 2005; IEA 2008; Vanegas 2003). They need assessment approaches that give detailed financial and environmental impact quantification to help them choose between competing options and provide input into future generations of integrated management systems such as Building Information Modelling (BIM). These options, for example, include material choice for refurbishments or operational decisions for delivering comfort services to occupants. Building owners and operators also need to be able to test building resiliency to both exogenous pressures and interior (use) changes. Buildings must be able to avoid, adapt or recover from external events such as climate change, constraints in energy supply or changes to regulatory standards and interior changes in use. This dissertation investigates the application of life-cycle approaches to evaluate performance for buildings in terms of financial and environmental impacts.

This introductory chapter gives an overview of the current approaches to evaluating high performance buildings and discusses how life-cycle approaches can provide design insight by measuring and simulating the effect of internal and external drivers on building systems over long periods of time. Various applications of life-cycle approaches are summarized, including benchmarking and tracking progress towards design targets. The strengths and limitations of life-cycle approaches are discussed in terms of how uncertainty places boundaries on accuracy, precision and comparison. A key application for life-cycle approaches is decision support during the design process. Challenges and applications for life-cycle approaches are introduced within the framework of the integrated design process (IDP). The use of life-cycle modelling is outlined within the context of UBC's various strategies for sustainability, which all use IDP, including use for measurement and verification of LEED and UBC's new regenerative building. The chapter closes with a list of four overarching research questions, along with an overview for the structure of the dissertation.

1.1 Challenges to building assessment

Building impact assessment models must produce metrics that are broad enough to integrate impacts from different sources, yet detailed enough to give direct quantification of effectiveness within the various dimensions of sustainability; society, economy and environment (IEA 2011; Helgeson & Lippiatt 2009; Weikard & Zhu 2005; Cole & Howard 2004; UNEP 2007; Kaatz et al. 2006; Schwarz et al. 2002; Lützkendorf & Lorenz 2006; Dasgupta 2008; O'Sullivan et al. 2004; Scofield 2002; Sumaila & Walters 2005; Turner & Frankel 2008; Lstiburek 2008). This is challenging because building use is not static; occupant demands mean that they vary in use and intensity. They are constantly being altered or retrofitted, and experience technological churn, with each of these changes having varying metabolisms, or cyclical rates, that reflect functional changes within the building (Brand 1995). Updating fixtures, furniture or IT systems has a fast rate of change, whereas upgrades to a building envelope have slow rates of change. Additionally, the way building services are accessed and used by occupants depends on how users interact with the building systems. Impacts due to changes in occupant behaviour are critically important to the overall performance of buildings (de Dear & Brager 2001). As well as occupancy patterns, intensity of energy use for process loads and plug loads are highly influential to overall performance. A recent study of 8,648 buildings in New York City shows that, despite improvements in building technologies, newer buildings are not showing consistent improvement over older buildings (Butts 2007; Hsu & Kontokosta 2012). The technological trend of newer buildings to use active rather than passive systems is, surprisingly, not resulting in efficiency improvements. The Plan New York City (PlaNYC) study shows that consumption is correlated to worker density, scheduling and intensity of use rather than building age. Building use, therefore, is a stronger determinant of performance than the technological improvement of structural and enclosure systems over time. This counter-intuitive trend, from a life-cycle view, is explored in Chapter 3. The strong dependency on occupant use presents a serious challenge to assessment in general since most protocols that inform rating systems such LEED, BREEAM or CASBEE, focus on building infrastructure rather than operation. The challenge for building assessments is in identifying how building design can most effectively minimize impacts and ensure occupant use as intended, while providing high quality indoor environments.

Overall, building designers and operators, particularly owner-operators, need to know how their buildings will perform under different operating conditions (Lowe et al. 2006; Bordass & Leaman 2005; Cohen et al. 2001). Impact is correlated to both interior (occupant driven) and exterior (exogenous driven) changes over time. Understanding how these affect overall life-cycle performance is key to evaluating resiliency of building design.

1.1.1 Interior drivers of impact

Ideally, a building designed to be adaptable will cope well with different types of occupant use. Studies show that small incremental changes in occupant behaviour have proportionally large changes to energy and water usage (Bourgeois et al. 2005; Clevenger & Haymaker 2006; J. E. Petersen et al. 2007) . While energy modelling of a building works well for predictable and ideal occupancy patterns, the actual behaviour of occupants is highly variable (GBN 2007; Nicol & Roaf 2005) and is rarely accounted for. Additionally, new and rapidly changing information technologies represent a new challenge to performance assessment. The increase of electrical consumption in buildings is partially blamed on the proliferation of IT devices (Swart et al. 2004; ECOS 2011). Despite the gains in efficiency per device, the number of devices in use has risen sharply, meaning absolute impacts have increased (Sanchez & Webber 2007) The implications for these metabolic rates are explored in Chapter 3.

1.1.2 Exterior drivers of impact

Buildings are susceptible to fluctuations in external air quality, utility resource availability and cost, all of which are highly unlikely to remain stable. Buildings are also susceptible to climate change (Börjeson et al. 2006; Roberts 2008). Global and local climate variability is highly likely to vary over the next 50-100 years which is within the lifespan of all new buildings under construction today (Levine et al. 2007). With energy consumption being strongly linked to ventilation strategies along with heating and cooling requirements (IEA 2011; UNEP 2007), climate change could lead to changes in consumption patterns and energy use.

Additionally, environmental costs are becoming significant. Pigouvian (environmental) surcharges, such as a Carbon tax, are becoming a persistent and long-term reality. For medium to large institutions, these taxes are significant costs over the long time frames associated with building life. Building owners and operators need assessment methods that will reveal the performance of buildings in terms of impacts arising out of these external pressures and map out how they are distributed over time (Schwarz et al. 2002; O'Sullivan et al. 2004; Helgeson & Lippiatt 2009). This shift towards performance based assessment methodology is explored throughout the dissertation, both in terms of financial performance in Chapter 2 and environmental performance in Chapters 3 and 4..

1.2 Performance based building assessment

Currently, there are many competing initiatives to support the adoption of 'green' building practices, including commercial green certification tools such as LEED™, BOMA Best (Building Environmental Standards), and Green Globes building rating systems. Rating systems, as exemplified by LEED, are prescription based point systems. However, they are of limited use as design tools. The output of a rating is not a performance assessment, but rather a claim of 'sustainable' building practices that is certified by a commercial third party. The prescriptive rating system can be useful as an easy-to-use guide, but has been criticized for diverting the attention of decision-makers towards 'point-chasing' and away from setting and attaining performance targets (Cole 2005; Wedding & Crawford-Brown 2007). However, LEED is slowly moving away from prescriptive measures and towards performance targets as exemplified by the move towards better measurement and verification practices. Unfortunately, operational improvements are not yet visible in the literature. Studies have shown that the LEED® rating system has certified buildings with highly variable performance profiles (Scofield 2002; Turner & Frankel 2008; Lstiburek 2008). Ensuring performance requires a new approach — moving away from lists of disconnected technologies and strategies, towards a whole-building integrated performance approach (Horman et al. 2006). However, for 'performance' to be meaningful to a building's stakeholders, it must conform to local expectations of impact reduction and uphold the social utility, comfort, health and safety of all future building inhabitants (Cole & Howard 2004). Cole et al. (2001) and Brager (2005) stress the importance of considering occupant well-being at design outset. This includes provision for adaptive and interactive controls (Brager and de Dear 2000). Without due consideration of inhabitant behaviour, even low energy building performance will be compromised by inhabitants attempting to attain an acceptable level of comfort (Brown 2009).

While science based approaches lead to rigourous assessments, there are sharp limits with respect to value and cultural influences. While such influences are beyond the scope of this dissertation, they should be acknowledged as a limitation of quantitative methods such as LCA. Throughout the dissertation, no cultural or value-based considerations were formally analyzed or directly considered. Finally, it should be noted that highly structured assessment methods may constrain the solution space for novel design. As Cole (2004) points out, standardization can prevent innovative approaches taking root. The potential hazard of design constraint motivates a careful characterization of the meaning of performance metrics. Relevancy to design emerges when metrics are defined collectively with building stakeholders and decision-makers working to, or beyond, best-practices and benchmark standards, and most importantly, pinpointing the appropriate performance metrics that they regard as collectively important. The ICT section of Chapter 3 is exemplary of this approach where participatory stakeholder involvement helped to define best-practices and environmental targets.

1.3 Life-cycle approaches for buildings

Evaluating the performance of long-term building operation has been; typically most assessment methods only capture up-front impacts. In the case of financial impacts, the focus is on construction cost. Similarly for environmental impacts, the focus is on the immediate impact of construction. For example, LEED rewards careful management changes to site conditions, material choice and reuse, but provides much less guidance on long-term impacts. Capturing long-term impacts, and thereby whole life assessment, requires a different approach. As suggested by the now disbanded National Round Table on the Environment and the Economy (NRTEE) in 2012, life-cycle approaches offer a useful toolbox to explore and model whole-life processes, and are recommended as support tools for decision-making in the design phase of buildings (NRTEE 2012). These tools can augment building assessment tools, and have been partially integrated into the BRE Environmental Assessment Method (BREEAM) and GreenGlobes, and more recently into a pilot version of LEED v4. A utility of life-cycle tools is that they allow the analyst to find the relative impacts of different life phases (Cassidy 2005). However, the correct use of life-cycle tools is as a *comparative* analysis between competing solutions. The results should not be used as an absolute indicator of impact, but rather only to determine side-by-side magnitude of impacts. Life-cycle approaches are also becoming prevalent for benchmarking and standardizing performance. In particular, life-cycle environmental analysis is appearing in many building assessment systems including Green Globes and LEED v4. The use of benchmarking for life-cycle approaches is discussed in detail in Appendix A.1

1.4 Current life-cycle tools

Life-cycle tools in current use are life-cycle environmental analysis (LCA), life-cycle costing (LCC) and social life-cycle analysis (SLCA). LCA and LCC have been under development since the 1960s and have been formalized by the International Standards Organization (ISO) 14040 series (from 1997 to 2002) for LCA and ISO 15686 for LCC (ISO 2006a; ISO 2004). SLCA is an emerging approach that resembles ISO 14040 in structure, and holds promise for reporting impacts to human well-being along international supply chains (MO'Brien et al. 1996; UNEP 2009). SLCA is not used in this research, which exclusively focuses on LCC and LCA.

1.4.1 Life-cycle environmental assessment

The studies undertaken in this research are based on process LCA which, in contrast to economic input-output LCA, is based on physical inventories of building materials and converted to impacts by segmentation, allocation and characterization of industrial outputs. The limitations of LCA are well-known; 'impacts' are not actual, but only potential and based on approximations of material flows and supply chains. Most methods also average impacts at a global scale, which means that while an impact, such as lake eutrophication effects, is calculated, the exposure pathway and impact on specific regional or watershed based ecological systems is ignored. Other approaches such as ecosystem services are informative for more granular and localized environmental assessments (Luck et al. 2012). In addition, the uncertainties generated by LCA are varied and can be large in magnitude. Huijbregts (2002) identifies six different types of uncertainty and suggests that final LCA results may not be an accurate representation of absolute impacts.

The outputs of LCA studies — termed life-cycle impacts analysis (LCIA) — have multiple attributes, often with eight or more categories considered. Chapters 3 and 4 consider the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) impacts, which are the EPA's only approved method to show the multiple-attribute impacts for LCIA (EPA 2006). The bulk of this work is centered on UBC which, like most public institutions in British Columbia, has an interest in reducing energy and Global Warming Potential (GWP) impacts, both of which incur financial costs. The bulk of the analysis in Chapters 2, 3, and 4 therefore focuses on primary energy impacts and IPCC 2007 CO2eq.

1.4.2 Life-cycle costing

As a measurement tool, life-cycle costing attempts to evaluate the costs for each year of life phase and aggregate them into a single score — namely total cost of ownership (Fuller & S. Petersen 1995). This single impact is in contrast to LCA's multiple attributes. Life-cycle costing is often used to find the pay-back time of capital investment. In the case of buildings, the tool is most frequently used for finding the return on investment for long-term building interventions such as energy upgrades. Additionally, the tool has the benefit of being able to compare the cost though time with corrections applicable to the time-value of money. These include discount rates, inflation rates, and the approximated lifespan of building components.

The limitations of life-cycle costing are related to the difficulty in handling long-term costs. Many economic macro-scale changes are not smooth, but instead discontinuous and unpredictable. Modeling the influence of macro scale changes on multiple decades of accumulated building cost, with respect to timing and magnitude of step-wise changes is challenging. Construction price escalation costs have been recently observed to vary between -10% to +14% per annum in British Columbia, in a narrow three year window. Another key issue, which has been the subject of much analysis, is the choice of the appropriate discount rate (Weikard & Zhu 2005; Dasgupta 2008; Sumaila & Walters 2005; Frederick et al. 2002). Opinions vary across a spectrum of market rates and social time preference rates. Given these different views and the sensitivity of final results to this choice, a sensitivity test approach to this question was adopted here. A final concern has to do with the practice of continuous discounting over long time periods. Since even low discount rates create very large effects over periods of several decades, the meaningfulness of such calculations has been questioned. Chapters 2 discusses how LCC can be used to find the total cost of ownership for a whole building and the chapter contains a detailed discussion of uncertainty, including the implication of construction price variation, as noted above.

1.5 Limitations and difference between LCA and LCC

Despite superficial similarities of the temporal framing of LCC and LCA, there are methodological differences between the two methods (Guoguo 2008; DLMC 2006). LCA generally ignores the time value of impact release. For example, it does not consider whether one kilogram of carbon dioxide released today has the same impact as one kilogram of carbon dioxide released in 50 years. In contrast, life-cycle costing takes into account the time value of money via escalation rates and discounting. These rates vary according to investment type and macro-economic trends. The fundamental difference in time-value accounting between the two approaches has been a road-block for integration. This research does not attempt integration into one tool, and instead uses the models separately to inform an overall discussion.

A second key difference is that LCA necessarily adopts a multi-attribute approach, while LCC is based on a single metric (financial cost, usually expressed in real terms). The attributes delivered by LCA range across a wide array of environmental impacts. These include 8-15 different environmental 'mid-point' impacts, ranging across various damages to the atmosphere, aquatic and land systems. The extra information that LCA produces can be a significant burden on decision-makers. In contrast, LCC produces a single metric – the total cost of ownership – and is relatively simple to integrate into a decision-making process.

Table 1.1 shows the key differences in the methodologies.

Table 1.1 Summary of key difference between LCC and LCA

Differences	**LCC**	**LCA**
Focus	Financial flows	Material (physical) flow
Discounting	Opportunity cost	None
Inflation	Escalation rates	None
Metrics	Single attribute	Multiple attributes

Furthermore, life-cycle approaches are highly simplified methods of analyzing supply chains. Both LCC and LCA modelling depend on linear and one-to-one relationships for supply and demand of components and the summation of impacts. While such assumptions lead to tractable problem solving, they trigger various types of uncertainty which, due to the complexity of buildings and numerous resulting supply chains, is unavoidable.

1.6 Uncertainty in life-cycle approaches

Uncertainties for real world systems are inevitably large, multi-dimensional and hard to define (Swart et al. 2004). In order to use uncertainty results intelligently in decision-making, Norris (2002) focuses on the need to declare and 'unpack' them explicitly (Norris 2002). Hisschemoller et al. (2001) suggest that, for decision-makers to contextualize uncertainty, they must be made aware of underlying assumptions that define variability and unknown quantities. Even if the reliability of the conclusions is not sufficient for decision-making needs, uncertainty analysis will also help to identify areas of decision-risk (Hisschemoller et al. 2001). Chapter 2, the LCC of CIRS, explores the relationship between reliability, uncertainty and financial decision-risk.

In the case of LCA for buildings, there are several important characteristics that decision-makers and modelers must examine. Products and processes in the LCA context are particularly subject to errors due to unknown futures for long-lived components such as building envelopes. (Funtowicz & Ravetz 1990) have proposed a general classification for uncertainties. They collect all sub types of error into three broad categories: data uncertainty, model uncertainty and completeness uncertainty. From this starting point Huijbregts (2002) subdivides these groups into six types for LCA modeling (Huijbregts 2002). Uncertainty and variability are classified into (1) parameter uncertainty, (2) model uncertainty, (3) uncertainty due to choices, (4) spatial variability, (5) temporal variability and (6) variability between sources and objects (Huijbregts 2002; Heijungs & Huijbregts 2004). While it is beyond the scope of this work to examine uncertainty to this level of detail, it is worth noting that the distinction between types of uncertainty is important for both modeler and decision-maker, because unknown error, as a lack of knowledge, may require assumptions that are greatly dependent on value-choices. For example, ISO (2006) indicates that proxies may be used to substitute missing data. Choices for proxies, such as economic figures, may either satisfy the values of the modeler or the decision-maker but not necessarily both of them. Therefore, the acceptability of the final result may be called into question by either the modeler or stakeholder on grounds of validity. In the case of models constructed for this dissertation, the author has worked as closely as possible with stakeholders and decision-makers to ensure that all assumptions are acceptable. Furthermore, stakeholders with relevant expertise were directly involved with the modeling whenever possible, and their knowledge was used to either confirm data proxies or provide expert judgment.

To formally explore uncertainty, various statistical tools may be applied to support claims to validity. Statistical tools can examine the consequences of errors that propagate through life-cycle models. The most commonly used tools are Monte Carlo (MC) simulations that work by applying randomly generated numbers selected from bounded distributions to key variables. The outputs of the simulation are probability distribution functions representing the spread of possible outcomes. However, there are methodological limitations to Monte Carlo. While MC can model risk appropriately, insofar as probability distribution functions (PDF) are known, it struggles to handle uncertainty (Lloyd & Ries 2007). An early draft of Chapter 2 contained a full MC simulation of the energy inputs for CIRS based on the original design energy model. A PDF was generated from 20 years of UBC utility cost variability data which produced a positive skewed distribution. However, the resulting MC energy cost distribution, based on 1000 simulations, proved to be completely wrong; the actual performance of CIRS was outside the bounds of the MC input parameters. The model was predicated on CIRS performance, at least nominally, operating as expected by the eQuest energy design model. The MC failed to capture the uncertainty attributable to the final performance of CIRS, which proved to be higher than expected due to procurement challenges in guaranteeing integration of the heat recovery system. Failure of MC due to non-technical issues is similarly reported by Rotmans & van Asselt (1998). MC can be misleading to decision-makers in that it can give the impression that possible error deviations are known, when in fact they are unknown. Chapters 2 discusses uncertainty in terms of implications to stake-holders rather than focusing on determination and reduction. The emphasis in this dissertation is therefore on communicating the aspects of uncertainty that have greatest influence on the model. The influence of the highly uncertain variables on the model are analyzed with sensitivity and scenario analysis.

1.6.1 Scenario analysis

In the face of irreducibility of uncertainty, Asselt et al. (1996) propose that instead of seeking a definitive resolution of uncertainty, modelers should be thinking in terms of "managing" uncertainty. Asselt suggests that modelers engage a wide variety of model perspectives as their central task for communicating their findings. Nowotny and Gibbons suggest that trying to reduce uncertainty, as an end in itself, is not always the most efficient use of resources (Nowotny et al. 2001). For models that attempt to replicate complex systems, the unrelenting chase for a perfect model yields smaller and smaller returns of precision and accuracy (Nowotny et al. 2003). Rather than attempt to reduce uncertainty, different methods can be brought to bear on the analysis of long term impacts (Pesonen et al. 2000; Norris 2002). Pesonen, Ekvall et al. (2000) and later

Hertwich (2005) and Porta (2008) propose using scenario techniques specifically for LCA (Hertwich 2005; Porta et al. 2008). Scenario analysis is also recommended as an approach that allows decision-makers to gain advantage through flexibility, 'surprise' avoidance, and proactive design (Nicol & Roaf 2005; GBN 2007). This is particularly pertinent to conceptualizing and engaging futures for sustainability (ECOS 2011; Swart et al. 2004; Roberts 2008; Börjeson et al. 2006). Pesonen (2000) defines a scenario in LCA studies as a description of a possible future situation relevant for specific LCA applications based on specific assumptions with regards to different choices of design. Pesonen suggests the best approach for integrating scenarios is to include them in every step of the LCA process through the methodological stages outlined by the ISO standards (ISO 2006a; ISO 2006b). In this dissertation, scenario analysis was used mainly retrospectively; however the IT analysis in Chapter 3 involved bringing decision-makers onboard at the beginning of the problem formulation and follows Pesonen's scenario development process. The IT model was constructed by involving input from stakeholders and the constructions of IT scenarios were formulated with ongoing participation.

1.7 Life-cycle approaches for decision-support for building design

Decision-making may be described generally as a procedure where, (1) a problem is formulated, (2) design alternatives are formulated, and (3) a choice is made between alternative solutions to the problem (Tillman 2000). The design of buildings is reflective of the needs and goals of the building developers, architects, clients and users. In the past, conventional design approaches to commercial buildings have been product oriented, with the design process viewed as a cascade of high-level developer decisions flowing linearly down to building construction. Approximately, in sequential order, the conventional process sequence is from client to building developer, and on to architect, engineer, and finally to construction (Pearl 2004). This fragmented procurement path has led to a host of operational problems including increased costs due to energy inefficiency and social costs due to sub-standard indoor environments (iiSBE 2004).

For the successful implementation of performance targets, a design process is balanced between different types of expertise and stakeholder needs. In building design, who, when and why each participant is involved depends on the project scale, priorities of the developers, tenancy requirements and, for larger public projects, impacts on the community. Critically, the roles and intentions of participants, and the depth of involvement, are governed by a choice of whether to build to conventional standards or to green standards (Cole 2005). The type of decision-support enrolled in the participatory design process is typically problem-centered and is defined by stakeholders and guided by appropriate expertise (Robinson et al. 2006; Carlsson-Kanyama et al. 2008).

Decision-support for life-cycle approaches is a structured, typically model-based, approach to problem solving with a primary goal to support decision-makers to identify their concerns and help them find the ‘right’ choice. A summary of the use of life-cycle approaches in decision-support is shown in Figure 1.1.

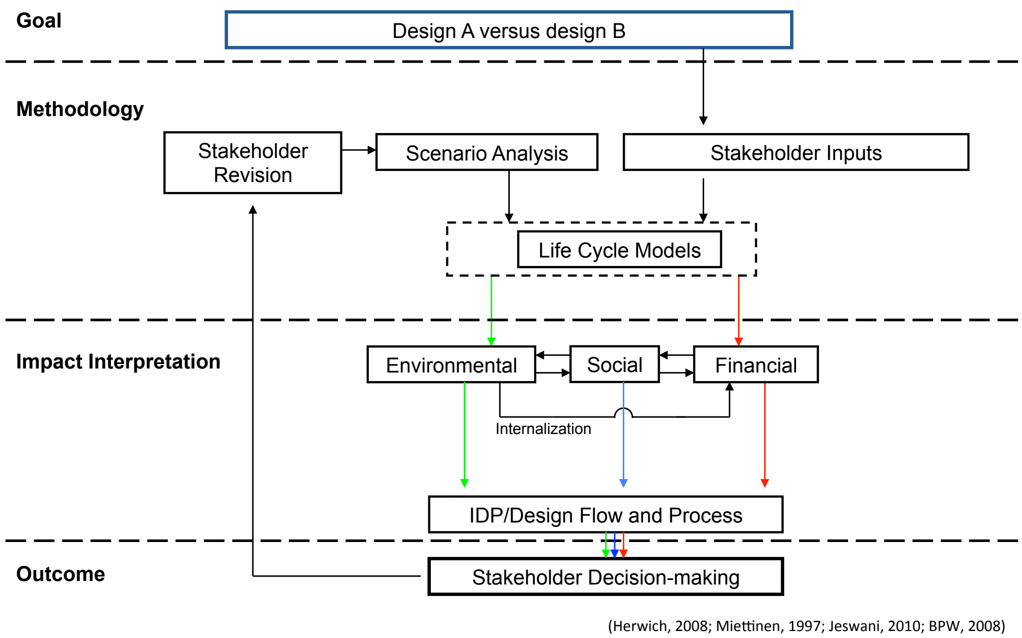

Figure 1.1 Decision flow for life-cycle approaches for buildings.

A favoured method for building a decision-making interface for life-cycle models is multi-criteria decision analysis (MCDA) (Hertwich & Hammitt 2001; Seppala et al. 2002; Roulet et al. 2006; Rowley & Peters 2007; Jeswani et al. 2010). MCDA can be regarded as an aid to integrating scientific measurement with value judgment, and coherent management of subjectivity (Stewart 1992). MCDA allows a decision-maker to observe the performance of multiple criteria side-by-side while being able to express preferences, or subjective level of importance, for each criterion individually. This enables a decision-maker to interpret a MCDA best-choice result as a subjective indicator of the collective strength of various preferences. A full decision-support analysis is beyond the scope of this dissertation, but details for a UBC tailored decision-support system along with a discussion for applicability with the Integrated Design Process are detailed in Storey (2010).

1.7.1 IDP decision-support with life-cycle approaches

The Integrated Design Process (IDP) is becoming the standard design practice for LEED buildings in North America. IDP encourages all major stakeholders and external expertise to work together with a facilitator towards a plan for achieving project goals and outcomes (iiSBE 2004). IDP is a cyclic flow of meetings during which the design team works to devise, express and understand the design goals of the project; it provides a charrette forum to find innovative solutions to site-specific design problems. IDP, as developed by iiSBE and Perkins+Will, has integrated many of the key process requirements for green building design (BP&W 2007a; BP&W 2007b). The integrated design process has become the dominant procurement process of ‘green buildings’ for the design phase. The novelty of the IDP process is in the concurrent participation of the various architecture, engineering and construction (AEC) professionals who are encouraged to jointly participate in design charrettes. This round-table format enables considerable cyclic iteration early in the design phase, with a view to reducing the frequency of change-orders during the construction process. While IDP supports and encourages innovation within the charette format, there have been recent reports of the difficulty in carrying through many aspiration design solutions into successful building operation. Fedoruk (2013) points towards a significant performance gap in CIRS due to the inability of the IDP process to extend beyond the design phase. Alternate models of building procurement are suggested as better solutions to ensuring high quality building performance. This includes Integrated Product Delivery which is championed by the Lean Construction Institute. The Integrated Product Delivery structure uses a team approach to build a risk/shared reward system that focuses on solutions to avoid breakages in the procurement cycle (Baiden & Price 2011; Vibaek 2013).

Life-cycle approaches have struggled to be included in IDP due to the lack of tool support and the high level of expertise required for execution. Whereas LCA tools such as GaBi™ has been integrated into SolidWorks™ for real time impact analysis during design, LCA for buildings requires additional steps, like material take-offs, which involve specialized analysts and protracted periods of time. Focusing effort at the beginning of the procurement cycle, before major structural decisions are undertaken, has enabled the successful use of LCA for design. A screening LCA for the structure of CIRS was completed by Perkins + Will early in the IDP process and was useful for informing the decision for the extensive use of wood in the structure. In this context, a screening LCA is a preliminary study that makes simplifications and assumptions to create a rapid prototype model to gain an overview of key determinants in the design process. For CIRS, a model was produced when building massing was still being developed and the screening model was used to compare the impacts of various structural materials.

The life-cycle studies in Chapter 2 and 4 were mainly completed as retrospective studies for use as critiques of the original design decisions. An exception is the LCA IT analysis in Chapter 3 which was completed during the design cycle for CIRS and is a good example of the proper use of LCA providing data concurrently within a decision cycle.

1.7.2 UBC context

UBC has endeavoured to use the triple-bottom-line approach within the context of the Integrated Design Process (IDP). UBC campus now hosts at least six 'green buildings' constructed to LEED® Gold standards, many of which used the IDP. UBC also has firmly committed to hard targets. UBC guidelines require mandatory diversion of 75 per cent of construction waste for residential construction, and divert 50 per cent of construction waste from landfill for new institutional buildings. Additionally, all buildings must achieve a minimum LEED® Gold or equivalent rating. UBC has committed to reduce campus-wide GHGs by an additional 33 per cent from 2007 levels by 2015, reduce 67 per cent below 2007 levels by 2020, and finally eliminate 100 per cent of GHGs by 2050. Attaining these targets is a major technical and financial challenge for decision-makers at UBC (Robinson, 2013a). Controlling the long-term cost of carbon emissions is rapidly becoming a high priority for public institutions across Canada. British Columbia has recently levied a carbon tax which applies to all end-use GHG emissions in the province. An additional burden is shouldered by large public institutions and government agencies which must purchase off-sets to ensure carbon neutrality. The tax rate is equivalent to CDN$25/tonne for emissions, and mandatory offsets are priced at CDN$30/tonne. In 2011, UBC paid over $3 million in Carbon Tax and Pacific Carbon Trust (PCT) offsets.

This financial burden has spurred UBC to pioneer the use of innovative demand side GHG reductions within the campus building stock to reduce both operational and embodied carbon. Operational demand strategies include renovating older buildings and constructing all new buildings to LEED Gold certified (with a minimum number of 10 energy points) green building standard. UBC is also interested in reducing Scope 3 emissions, currently not taxable under the BC Provincial rules, to show leadership and institutional responsibility. For the UBC building stock, Scope 3 covers all embodied carbon emissions.

Life-cycle approaches are being engaged at UBC — two separate models are in use: life-cycle environmental impact estimator (Athena EIE) and a life-cycle costing calculator built by UBC Infrastructure Development (ID LCC). Athena EIE has been used extensively to calculate embodied carbon emissions. The combined life-cycle models currently calculate thirteen outputs, with metric selections from a broad spectrum of simulated environmental and economic impacts as recommended by the International Standards Organization 21931-1 (ISO 2010). These 13 variables represent the currently available quantified core attributes that are analyzed in this dissertation (shown in Figure 1.2).

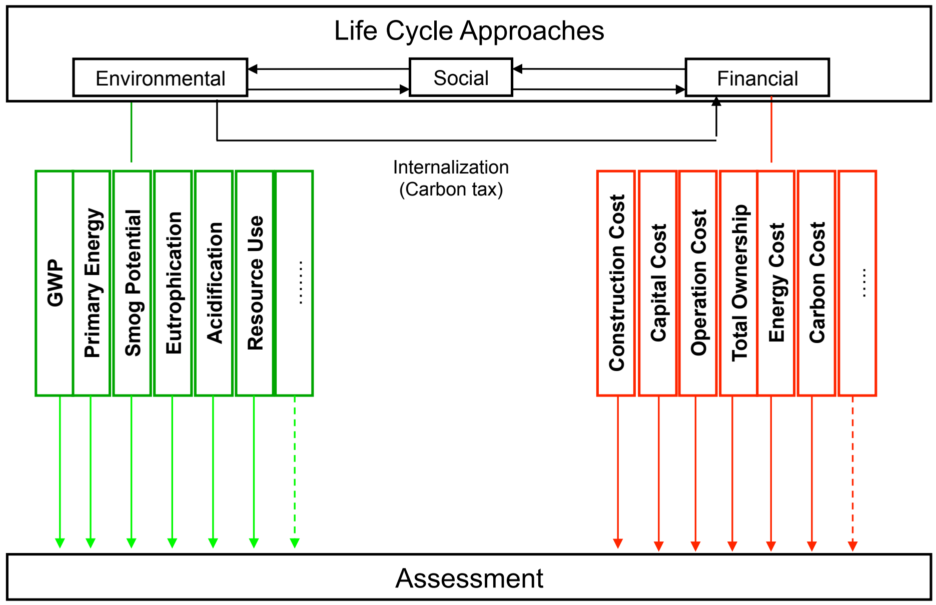

Figure 1.2 Metrics analyzed within dissertation research studies.

LCA and LCC have been used most extensively during the design of the Centre for Interactive Research in Sustainability including use early in the IDP design cycle to evaluate the carbon balance of the building's structure.

1.8 Regenerative standard and the Centre for Interactive Research in Sustainability

The Centre for Interactive Research in Sustainability (CIRS), a 5640 m^2 research facility completed in August 2011, is UBC's first attempt to construct a regenerative building. Regenerative design, as defined by UBC, uses construction and operation of infrastructure to create positive effects on ecological and human systems. Additionally, CIRS is an experimental building with many of its systems open for building science, technological research, demonstration and development. The intent of CIRS is markedly different from the current paradigm of green building design; CIRS seeks to promote regenerative systems to actively improve ecosystem health and reverse carbon impacts (Cole 2012; Robinson, Cole, et al. 2013b).

The advanced capabilities, functionality and design of CIRS were developed synergistically with other standards, included the Living Building Challenge (LBC). The building designers, with a team that included Perkins + Will Architects and Stantec Consulting Ltd., used LBC guides such as the 'Red List' – a prescriptive exclusion list of potentially hazardous building materials – to guide material selection. In terms of design, CIRS has unique challenges. For example, the lecture hall, which has a seating capacity of 450, created significant sustainability design challenges both in terms of engineering and architectural design.

The regenerative standard attempts to reach farther than current standards, as offered by LEED, which seek only to minimize impacts and promote 'less bad' development. LEED certification is based on the number of points that a building can score according to the quantity of green features installed. The technological approach taken by LEED is to 'add' sustainability features, such as large photo-voltaic arrays, to gain points. Although such approaches can yield incremental improvements, they are limited in their effectiveness. With the regenerative approach, as exemplified by CIRS, UBC is re-imagining buildings as 'better than before' development. Instead of 'less bad', a regenerative approach aims to improve both environmental and human well-being. However, like many standards that aim for above best-practices, the learning curve is steep. Pioneering buildings, such as the Adam Joseph Lewis Center at Oberlin College, have taken several years of operation and optimization, along with the addition of 27% more photo-voltaics, to attain their net-zero original aspirational targets (Scofield 2002; Scofield 2009). Furthermore, data shows that many high performance buildings, such as those reaching high levels LEED certification, are operating far below desired targets (Turner & Frankel 2008). However, little is known about the total life-cycle performance of these buildings. Using tools such as life-cycle analysis and life-cycle costing to evaluate high performance buildings is underutilized. Very little literature exists on, (1) the construction and use of net-positive design for reducing environmental impact of buildings, and (2) the development of life-cycle benchmarks for tracking the progress. To assist designers in evaluating performance-based sustainable buildings, this research provides informative case-studies that will assist decision-support for sustainable and regenerative design approaches.

1.9 Research objectives

The research objectives are focused on analyzing the relative life-cycle impacts of design decisions for high performance buildings. The work provides insight to evaluate both existing and future building designs. Four studies are undertaken to explore the impacts of CIRS, and selected features within CIRS, against best-practice standards. The research draws from two central methodologies of life-cycle costing and life-cycle analysis, to drill down on three main research questions:

1. What are the life-cycle cost impacts for a building constructed to CIRS 'standard' compared to LEED Gold?

2. What are the life-cycle environmental impacts for a building constructed to CIRS 'standard' compared to LEED Gold?
3. What are the community scale Carbon and Energy life-cycle impacts of LEED versus Conventional versus Regenerative designs for UBC core buildings?

1.9.1 Structure and overview

The research questions are answered in three manuscripts which are targeted for academic and industrial publication. The themes are focused on modeling the potential impacts of buildings systems as shown in Figure 1.3

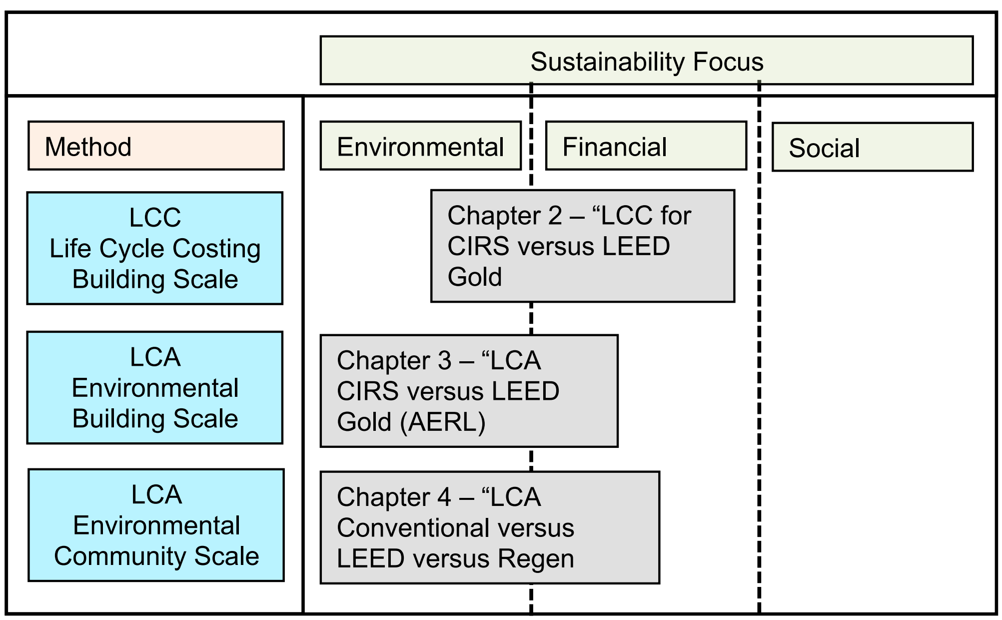

Figure 1.3 Dissertation overview and structure.
Three main themes in sustainability addressed over three research chapters using various life-cycle approaches.

Chapter 2 investigates research question ,1 and is a case-study comparing the total cost of ownership of CIRS with an equivalent building constructed to LEED Gold standard. The study derives a first-cost benchmark with an extensive study of recently built UBC

‘LEED equivalent’ buildings. The chapter concludes with a discussion of the use of LCC for analyzing resiliency and risk in building design.

Chapter 3 investigates research question 2, and is a case-study examining the same case-study buildings used in Chapter 2, but using life-cycle analysis to derive potential environmental impacts. The study leverages the benchmarking capabilities of the UBC LCA database. This recently developed UBC specific database enables high-resolution comparisons of cradle-to-gate impacts. The analysis includes recent data on information and computing technology systems for CIRS, along with a limited discussion of the impact of furniture and fixtures.

Chapter 4 investigates research question 3, and is a community scale study with a focus on life-cycle energy and carbon foot-printing. In contrast to Chapter 3, the study focuses on operational impacts, and utilizes utility consumption data for 70 Conventional Buildings versus 10 best practice (LEED Gold) buildings at UBC. The analysis explores how operational performance varies with respect to building age and building type. The operational data is integrated with embodied impact data from earlier chapters to give a direct comparison between cradle-to-gate and gate-to-grave impacts.

Chapter 5 concludes and summarizes the main findings and research outcomes. The conclusion draws together the strengths and weaknesses of life-cycle approaches along with applications for decision-making processes. The chapter closes with recommendations of research directions with regards to the use of life-cycle approaches for building design, along with policy recommendations for generating better building standards at UBC and beyond.

Chapter 2: Life-cycle Costing for a Regenerative Building: Challenges to Modelling the Financial Performance of the Centre for Interactive Research on Sustainability

2.1 Summary

A total-cost-of-ownership financial case-study of The Centre for Interactive Research on Sustainability (CIRS) building is evaluated for costs incurred in all phases of the ownership cycle, from cradle to grave. Life-cycle costing is used to compare the financial performance of CIRS to an 'equivalent' building built to a LEED Gold base-case. An 'equivalent' building is defined as a building constructed with an identical architectural program, size, and function as CIRS but with a construction and operational capability of a LEED Gold certified building. The construction cost of CIRS is calculated to be 28% more than the equivalent building but within two standard deviations of the variation of recently constructed buildings at UBC. This means that the cost of CIRS is within expected bounds of variation for comparable campus buildings. Longer time scales show an accumulation of operational savings for CIRS which enables break-even; however, the pay-back time is particularly difficult to model due to multiple uncertainties. Modelling is challenged not just by unknown uncertainties in long-term cost, but also by short-term difficulties in commissioning advanced and complex regenerative buildings. While the life-cycle model itself is useful for aggregating cradle to grave costs, the process of model construction is found to be useful for guiding decisions and highlighting areas of cost risk uncertainty and vulnerability in the procurement path. We conclude that

lifecycle approaches are useful for identifying risk and lead to more robust budgeting models for institutional buildings.

2.2 Supporting participation and acknowledgment statement

Data and modelling contributions: John Metras (UBC Infrastructure development), data contributions from UBC Properties Trust.

Decision stakeholders: UBC Infrastructure development, UBC University Sustainability Initiative, UBC Operations

Co-authors and peer review: Alberto Cayuela (UBC University Sustainability Initiative), John Metras (UBC Infrastructure development), John Robinson (UBC University Sustainability Initiative)

Mentorship: Professor Mark Monroe (Sauder Business School)

2.3 Introduction

When developers look at building procurement, they consider financial factors in great detail. For private developers, the focus is generally on first (construction) costs; however, for owner-operators the cost burden is distributed across the life-cycle of a building, from upfront soft costs, hard construction costs, through to operations, maintenance and capital renewal. Life-cycle costing is a method for capturing the total cost of ownership. This is a useful modelling approach where a cost premium, such as those typical of green buildings, may be required to gain operational cost savings over long time frames. The rapid uptake in LEED projects has triggered interest in calculating these initial cost premiums. Previous analyses have examined the incremental cost of

LEED Gold over conventional building; for example, Gluch (2004) and Baumann (2004) find office premiums of 7.8-8.2%. Davis Langdon data show an incremental cost increase of 1-10% for LEED building standards from Silver to Platinum (Morris 2007). More recent reports show similar premiums; (D'Antonio 2007) finds 1-6%, (Deloitte 2008) shows LEED premiums of 4-7% for schools in Alberta, (Mapp et al. 2011) shows a LEED premium of 2-3% for banks, and Kats (2009) find most green buildings cost 0% - 4% more than conventional buildings, with the largest concentration of reported "green premiums" between 0% - 1%. A major review by the World Green Building Council of studies between 2002 and 2012 finds premiums ranging from -0.42 to 12.5% (WGBC 2013). However, few studies report full life-cycle costing results.

Recently, best practices benchmarking has improved in many jurisdictions. The minimum construction standard for public buildings in British Columbia, and many cities across North America, has shifted up to LEED Gold, rendering the 'conventional building' benchmark obsolete. With LEED Gold being the new minimum standard, the question about the cost of 'going beyond' LEED remains insufficiently researched. The significance of this study on CIRS is that, firstly, the total cost of ownership, or full life-cycle cost impact is calculated, rather than simply calculating and comparing construction cost. Secondly, LEED Gold is used as the minimum benchmark rather than a conventional building. This is appropriate, because many institutions are interested in moving toward higher performance standards, such as the beyond-best practices model of 'regenerative' buildings. Thirdly, we use empirical first-cost data to accurately set the cost of the LEED benchmark with respect to building area. The empirical model allows decision-makers to examine typical cost variance, not just average cost, with respect to building area. Finally, the challenges to constructing the models are discussed, including the technical difficulties in modelling long-term uncertainty and risk. The utility of understanding and mapping risk in a financial model is particularly important to resilient budget cost and sharing.

2.3.1 Navigating long-term costs and savings

By levelising costs from different life phases, Life-cycle Costing (LCC) is one of the most useful methods for long-term budgeting for buildings (Issa et al. 2010; Wolff 2006). The National Institute of Standards and Technology (NIST) definition of LCC exemplifies the general scope: it is a method of accounting for all directly related expenditures from cradle to grave including construction, capital renewal, maintenance, operation and deconstruction costs (NRCan 2005; Fuller & S. Petersen 1995). Life-cycle approaches are particularly pertinent for sustainable building design. The Royal Institution of Chartered Surveyors (RICS) suggests that it is a critical component of the sustainability equation, a key input into the broader systems context of sustainability (Turner & Frankel 2008; RICS 2005). To this end, the BRE Environmental Assessment Method (BREEAM) acknowledges the usefulness of ISO-compliant LCC for sustainability by crediting use in their rating system. The USGBC are also acknowledging the importance of life-cycle approaches in building design with LCC references in their National Research Green Building Agenda (Newsham et al. 2009; USGBC 2008).

Unfortunately, both private and public developers have underutilized LCC as a mainstream tool because they are primarily concerned with reducing first costs. The current practice for building procurement is to design and construct a building at least cost for a client in the shortest possible time frame. The current focus on first cost means that very little attention is focussed on how the building will operate 10, 25 or even 50 years in the future. The direct consequence is that developers and clients have no measure of building resilience to future budget 'surprises' caused by energy price fluctuations or climate change. Developers typically do not engage in a long-term cost analysis unless they can derive direct financial benefit from down-stream savings or gain an edge in the real-estate market. Any long-term operational inefficiencies are relegated to future tenants or owners. This 'split incentive' gap is an obstacle to sharing financial benefits gained from high operational performance. Bridging the 'gap' is challenging not only for both private developers, but also owner-operator developers at public institutions (Morris 2007; WBCSD 2008).

UBC, as an owner-operator, has taken steps towards bridging the gap with this study, which reports on the use of a scenario-based LCC model, with participation from multiple stakeholders. The stakeholders include representatives that are financially responsible for the building at all life phases. A case-study building is assessed - the Centre for Interactive Research on Sustainability (CIRS) - a beyond best practice building and compared against a LEED Gold building benchmark. Few financial analyses have been completed for beyond-LEED construction practises; by comparing CIRS with LEED Gold, future builder-operators will have a comparative financial map that will explicitly show where costs and savings are located. To this end, budgetary costs are evaluated at all life phases, along with the impact of long-term operational uncertainties by using scenario analysis to create 'what-if' energy futures to test financial resilience to unforeseeable change. The analysis uses empirical data for comparing first-costs, and simulated data for operational and capital renewal costs. The latter part of the study focuses on energy consumption and cost, a priority for UBC which is simultaneously exposed to carbon taxation and an electricity transmission constraint for incoming campus supply. This study offers an opportunity for both owner-builders and operational managers to observe that they can mutually co-benefit from resilient and high performance design by identifying cost savings and financial risk reduction throughout building lifespan. It is the first key step in a series of actions that take us closer to attaining a sustainable future.

2.3.2 CIRS context

During the design process, the IDP team aimed at net positive performance goals. For example, performance targets where identified as net positive on structural carbon storage (more carbon stored in the building structure than emitted for the construction process), and net positive on operational carbon (CIRS operational goal to reduce net carbon emissions for the campus). There are key costs and savings associated with attaining each performance target. How to quantify and control these costs over long time frames is a critically important question for owner-operators such as UBC. Risk mitigation, in terms of understanding uncertainty with regards to construction costs and operational costs, is a high priority for the financial management of novel developments like CIRS. To map uncertainty, two main strategies are taken. Firstly, the cost premium is determined against a sound benchmark of previous construction projects. Rather than relying on modelled or generic first-cost data for LEED, a benchmark is generated from known local costs from publically available UBC data on 11 green buildings constructed at the Point Grey campus between 2000-2011.

Secondly, long-term operational and upgrade costs are derived from an advanced costing tool developed by the Infrastructure Development department at UBC. This tool contains a high resolution of life-cycle costs, including local campus union costs for upkeep, building maintenance, scheduling, janitorial upkeep and utility cost. Where data is unavailable, such as for maintenance schedules of CIRS' new technologies, expert judgement is used to inform assumptions (explicitly described and later tested in a sensitivity analysis).

2.4 Overview of life-cycle costing

Life-cycle Costing is the most conservative of costing methods and is restricted to measurable and recognized direct and contingent expenses (D'Antonio 2007; Davis Langdon 2007; OGC 2007; Aouad et al. 2003). This study adheres to guidelines specified by the National Institute on Standards in Technology (NIST) which are based on Federal Energy Management Program (FEMP) accounting methods (Kats et al. 2003; Fuller & S. Petersen 1995). These are typically used for long-term planning for institutional and governmental projects. NIST standards are closely aligned with ISO/DIS 15686-5 (ISO 2004) and ASTM E917 - 05e1. As specified by NIST, LCC evaluates budgetary impacts for each life phase, maps them into constant dollars and projects them into a net present value (NPV) using locally accepted discount and escalation rates. The utility of LCC is that it can take costs that are unevenly distributed in time and aggregate them into a single number called the 'total cost of ownership'. The primary purpose of life-cycle costing is to compare building alternatives and to identify the option with the greatest savings (Lucuik 2005; GSA 2005). The process of producing an LCC model also facilitates dialog between financial stakeholders. An open and informed conversation about NPV costs between developers and operators is important for optimizing budget management. While the utility of an LCC study may be limited by model and data uncertainties, the *process* of modelling leads to deeper collective understanding of the broader cost context and encourages financial innovation.

2.4.1 Critique of LCC

The critique of LCC for building applications is split into three discussions: concerns about the ability to replicate actual building costs, the challenge of handling the time-value of cost/savings, and ambiguity regarding building longevity.

(1) The ability of LCC to replicate actual costs has been questioned with mismatches between modelled and actual costs. For example, Kshirsagar (2010) reports model-actual differences of up to 37 and 48% for construction and maintenance costs, respectively (Kshirsagar et al. 2010). The underlying factors driving these mismatches are widely reported. Korpi (2009) suggest that variability can be attributed to incomplete life-cycle reporting, estimating costs on a low level of detail, basing cost on expert opinion instead of

statistical data, and using deterministic estimates of costs instead of undertaking sensitivity analyses (Korpi & Ala-Risku 2008). Pelzeter (2007) discusses the importance of the method of calculation and, like Korpi, draws attention to the variability of model parameters (Pelzeter 2007). Some of the procedural issues can be successfully resolved by close adherence to NIST and ISO 15868-5 standards, which specify guidelines with regards to data handling and quality. However, many uncertainties cannot be removed; changes to building function, or systemic external changes driven by regulatory requirements are fundamentally unpredictable. LCC models have utility specifically for comparing competing design options, not for predicting actual cost.

(2) The time-value of costs, especially for modelling conducted over long time frames, has been shown to challenge LCC modelling. Models are highly sensitive to discount and escalation rates, which exponentially scale cost over time. Engineering cost approaches, such as those used by NIST, use market discount rates that are held constant over the modelling timeframe. Market rates, which represent the opportunity cost of private capital, are often high (>5% Real rate) and cause a rapid erosion of long-term costs and savings. An alternate approach is to use lower 'social' discount rate (3-4%) for public works to account for broader social purposes and environmental costs and benefits. Social rates often lead to a greater long-term value and rectify the short-term preference of private capital providers. Suggestions for application of this approach include the use of lower 'intergenerational' discounts rates

(Sumaila & Walters 2005), ‘weighted’ rates applied to processes that are irreversibly harmful to the environment (Hellweg et al. 2003), ‘dual-rates’ for projects with mixed environmental and market goods (Weikard & Zhu 2005), and declining rates to account for wealth and precautionary effects that are proportional to project time horizon (Gollier 2008). The impact of discount rates on pay-back should not have any bearing on the decision of which is the most appropriate discount rate to use. The rate should be selected based on the logic of the best discounting "equivalency" for these funds. In the case of a UBC campus building, the use of public funds within the context of the Ministry of Advanced Education requires the use of a nominal rate of 7.2%.

(3) By definition, a life-cycle approach implies that an analysis be completed until end-of-life; however, there are differences with regard to how this is defined. NIST stipulates a service life of 25 years, which is appropriate for energy systems but not necessarily appropriate for building systems and structures. For example, many UBC buildings are in excess of 50 years old, a lifespan not unusual for institutional buildings.

BREEAM acknowledges the limitation of the short service life thresholds and recommends a 60 year study period. ISO 15686-5 allows for up to 100 years or at least the foreseeable life-cycle need or occupation of the constructed asset. It references that variations on service life can also be guided by contractual liability, such as financing obligations. ISO 15686-5 states that service lives longer than 100 years are less relevant, because costs are likely to be insignificant beyond this point. In fact, for discount rates

>3%, operational costs and savings contribute very little beyond 50 years. There is also considerable field evidence that buildings are often removed before structural degradation causes end-of-life (ATHENA 2006). The Athena Institute shows that local area redevelopment, driven by factors such as rising land value, is a stronger factor than their physical condition in determining renovation or end-of-life, which leads to a conclusion that many buildings are retired with 'useful' life remaining.

This study follows ISO 15686-5 to remove procedural error, while accepting that the model is only being used to compare relative costs and not to generate absolute costs. With regard to the first critique, this analysis uses actual construction costs, not modeled costs. To address the second critique, alternate discount rates (3% and 5%) are analysed as scenarios while applying two feasible service lives (25 years and 50 years which extends the modelling window to 2037 and 2062 respectively). With regard to the third critique, the model developed for this study does not have sufficient data on the longevity and maintenance schedules from 2062 to 2112 and so the model timeframe is restricted by a 50-year cut-off. The literature reveals very little with regards to the long-term technological development and operational cost of CIRS' novel systems.

2.4.2 Uncertainty: sensitivity and scenario analysis for LCC

Uncertainty is an endemic feature of long-term costing, not only because of the difficulty of predicting the durability of building systems, but also because of functional, technological and regulatory evolution (Arja et al. 2009). For LCC, uncertainty may place practical limits on the ability of decision-makers to interpret results (Gluch &

Baumann 2004). LCC models should therefore be used as a comparative tool, not as a generator of absolute costs. There are no guidelines for the level of detail in terms of Class A to D, analysts are expected to provide as much detail as relevant for comparing the cost of design option within a single model. To examine uncertainty in our model, sensitivity analysis is used first to check for model uncertainty with an increment of 10% (as suggested by NIST) on key assumptions. Sensitivity analysis involves perturbing individual variables to explore their relative effect on the overall model result.

Secondly, scenario analysis is used to examine technical scenarios which can be useful in probing a building model to gain insight into the consequences of various design decisions (Goodall 2003). In contrast to sensitivity analysis, scenario analysis involves collecting bundles of variables and applying them collectively to the LCC model with an aim to quantify effects on the total cost of ownership. Our scenario analysis focuses on various energy-related 'what-if' futures. Calculating uncertainty beyond 25 years is difficult due to a multitude of interacting unknowns, and cannot be modelled stochastically. Scenarios include determining building resiliency to unexpected changes to carbon taxation rates and step changes in energy cost and supply. Quantifying the level of exposure to uncertain future utility costs is of particular interest to campus operations. Creating robust and resilient buildings is important to the long-term financial viability of buildings, especially with regards to operational costs.

2.5 Model approach and structure

The model approach and structure are based on input from an interdisciplinary LCC team with representatives from the UBC Sustainability Initiative (mission to accelerate regenerative sustainability in terms of academic, research and operational collaboration), UBC Infrastructure Development (mission to provide stewardship for all institutional facilities) and UBC Properties Trust (mission to develop and manage real estate assets for the benefit of the University). Each stakeholder has a common goal of sustainability, but different priorities for implementation. UBC Properties Trust prioritizes first-cost budget control and asset management, whereas UBC Infrastructure Development prioritizes operations, maintenance and quality of service. Their cooperation enabled this model to be constructed at a high level of detail.

The model is formulated for a four storey, mixed use, university building examined under two different construction standards: LEED 3.0 Gold and CIRS. Here, *LEED Gold standard* is defined as achieving 60-79 points, as defined by the USGBC for LEED 3.0. The *CIRS regenerative standard* is a locally derived level of performance that is beyond LEED Platinum and is closely analogous to the Living Building Challenge (LBC) standard. However, the regenerative standard differs from LBC on several key points; CIRS goes beyond LBC by being better than energy and carbon net zero, hence CIRS is attempting to *reduce* UBC's carbon and energy footprint. However, in contradiction to LBC rules, CIRS does not source all raw materials 'locally'; several key components of CIRS, such as lecture hall ancillary equipment, cannot be manufactured locally.

The operation costs for both CIRS and LEED standards are based on an in-house spreadsheet tool constructed by Infrastructure Development (ID) at UBC. The ID model contains an extensive catalogue of maintenance and capital renewal costs based on regional rates and local union-based labour contracts. Utility costs are based on the direct cost to UBC for water, sewage treatment, gas and electricity. Some of these rates are based on historical agreements between UBC and utility service providers. For example, electricity rates are based on a prescriptive electricity tariff, as regulated by the British Columbia Utilities Commission (BCUC) and the British Columbia electricity utility, BC Hydro (BCH 2008). However, other utility costs, such as for natural gas for steam generation, vary in accordance to commodity market prices. Additionally, externalities such as British Columbia Carbon Tax and mandatory carbon offsets are calculated, as required for all public institutions. Finally, residual value is not calculated because the University assets are not market accessible and hence do not have a commercial value in conventional real-estate metrics.

Table 2.1 shows a summary of costs included in the model, including component durability ranges and data quality. Costs are grouped and annualized by UBC operations (annual averaging of scheduled maintenance and predicted lifetimes). Overall, data quality declines for components that have long lifespans. Data quality declines over long periods of time, especially for some of CIRS novel technological systems which have unknown operations and maintenance (O&M) and capital renewal costs.

Table 2.1 Costs and data quality considered for modelling.
FF&E: furniture, fixtures and equipment, IT/AV: information technology and audio-visual equipment, GSHP: ground source heat pumps, M&E indicates maintenance and equipment upgrades and BoG: UBC Board of Governors.

	Data Source		**Cyclical Costs (Yrs.)**		**Data Quality**	
	Regenerative' CIRS	LEED Gold	Mainten-nance	Capital Renew.		
Construction						
Hard Costs	HeatherBrae	Survey	-	-	Good	
FF&E	BoG	Survey	-	-	Medium	
Professional Fees	BoG	Survey	-	-	Good	
Permits	BoG	Survey	-	-	Good	
Project Management	BoG	Survey	-	-	Good	
Commissioning	BoG	Survey	-	-	Good	
UBC IT/AV Allowance	BoG	Survey	-	-	Good	
Operation					**Short Term**	**Long Term**
Municipal Fees	UBC ID	UBC ID	-	-	Good	Medium
BC Carbon Tax	BC Gov	BC Gov	-	-	Good	Variable t>3
Utilities (thermal)	BC Hydro	UBC ID	-	-	Good	Variable t>5
Utilities (electricity)	BC Hydro	UBC ID	-	-	Good	Medium
Preventative Maintenance	UBC ID	UBC ID	-	-	Good	Medium
Grounds Upkeep	UBC ID	UBC ID	-	-	Good	Medium
Janitorial	UBC ID	UBC ID	-	-	Good	Medium
Cyclical Maintenance & Capital Renewal						
Exterior Enclosure	UBC ID	UBC ID	10-25	75	Good	Medium
Fenestration	UBC ID	UBC ID	20	75	Good	Medium
Roofing	UBC ID	UBC ID	5-10	20-30	Medium	Medium
Interior Construction	UBC ID	UBC ID	4-10	75	Good	Medium
Interior Finishes	UBC ID	UBC ID	4-10	40	Good	Medium
Conveyance	UBC ID	UBC ID	1	25	Good	Medium
Plumbing	UBC ID	UBC ID	2	40	Medium	Medium
HVAC Systems	Corix & UBC	UBC ID	20	40	Medium	Medium
Fire Protection	UBC ID	UBC ID	Annualized		Good	Medium
Electrical	UBC ID	UBC ID	Annualized		Good	Medium
Rainwater Harvesting,	Corix	-	Annualized	40	Medium	Poor
Solar thermal&GSHP	Corix	-	Annualized	20	Poor	Poor
Wastewater treatment	Corix	-	Annualized	20	Poor	Poor
Academic Upgrades	UBC ID	UBC ID	Annualized		Medium	Medium
Code Upgrades	UBC ID	UBC ID	Annualized		Medium	Medium
IT Upgrades	UBC ID	UBC ID	Annualized		Medium	Medium
M&E Upgrades	UBC ID	UBC ID	Annualized		Medium	Medium
Deconstruction Costs						
Demolition	UBC ID	UBC ID	-	-	-	Poor

2.6 LEED costs and assumptions

Energy Benchmark: LEED Platinum certification has been achieved by CIRS, and a whole-building energy model was constructed as part of the application process. However, for this study the benchmark building is defined as CIRS built to a LEED Gold benchmark, the mandatory minimum building standard at UBC. LEED Gold energy data is based on typical reported energy savings for similarly sized commercial buildings from recent studies. However, there is wide variation reported for actual performance of LEED buildings. For energy retrofitted and LEED schools in Toronto, Issa (2010) reports 37% more on electricity, but 41-56% less on natural gas. A National Research Council Canada study reports average energy savings of 20.2% for LEED Gold (NRCan 2005). The New Buildings Institute study reports an average 45% energy savings for LEED Gold (Turner & Frankel 2008), whereas (Newsham et al. 2009) reports on average, LEED certified buildings used on average 18-39% less energy. However, of the surveyed buildings 28-35% of LEED buildings used more energy than their conventional counterparts. It is worth noting that there is considerable uncertainty in the performance of LEED buildings with standard deviations in the region of 30-40%. For this study, it is assumed that the average LEED saving is at least 28% better than conventional standards, because UBC specifies that at least 5 points must be scored in energy savings (sensitivity variable #1).

Maintenance Benchmark: Other operational costs for LEED buildings are similarly plagued by uncertainty, mainly because of the relatively recent arrival of LEED standards and the lack of data on maintenance costs. To date, UBC has had some maintenance issues with LEED buildings and, for the model, a conservative approach is taken for maintenance costs[1]. For the LEED building it is assumed that maintenance costs will be on par with that of UBC's current buildings stock, as determined by UBC ID data (sensitivity variable #2).

Construction Cost Benchmark: The construction premium for LEED buildings has been shown to vary greatly between studies. As previously mentioned, these premiums vary between -0.42 to 12.5%. However, many of these studies are highly problematic, for two reasons. Firstly, all examine pre-LEED 3.0 (2009) buildings, and they do not differentiate between construction costs for earlier versions of LEED. Secondly, these studies do not clearly distinguish variations in cost premiums due to regional location and building type. To avoid the problematic assumptions of these studies, UBC's extensive data on construction costs is used to analyze 11 campus buildings built to LEED Silver and Gold or equivalent standards. Selecting the most appropriate comparison buildings was challenging, as the LCC project stakeholders had varying criteria for determining similarity. Eventually agreement was reached on methods to account for variance in building function and type. With the assistance of UBC Infrastructure Development, the construction costs for each building were itemized and specialized costs reviewed. Any costs that are highly specific to building function — for example specialized library or laboratory infrastructure — were removed. This review process was further complicated by the use of different accounting practises between projects, an endemic feature of most commercial procurement and tendering procedures (sensitivity variable #3).

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[1] Extra maintenance issues include a variety of issues related to minor retrofits for plumbing (e.g. AERL sanitation), Kaiser (ventilation and acoustics), AERL (acoustics), and Choi (leaking roof). However, the data does not clearly show whether these costs are more, or less, than for conventional buildings.

Finally, the eleven most comparable recent buildings and this data were used to create a construction cost baseline. These buildings were built in the period 2000-2011; construction costs were bought forward into NPV 2011 dollars using historical escalation rates. While net present value calculations using historical inflation data is standard engineering practice, it is not without challenges. (Hsu & Kontokosta 2012; Butts 2007) points out that there is not a single index that accurately describes the entire construction industry. Moreover, like many escalation indices, there is time lag with respect to cost changes that have already occurred. Finally, these indices cannot account for the substitution of equivalent products, because the prices of fungible products, such as concrete or wood, vary independently.

A remaining and persistent source of uncertainty is market fluctuations for escalation rates used to normalize construction costs over time. In particular, the Vancouver construction price index shows variations between 14% and -10% over the period 2007-2009, as shown in Figure 2.1. These extremes were driven by the 2010 Vancouver Winter Olympics construction boom and, while not unheard of, are fortunately very rare events. Buildings that were tendered and constructed over this period had costs fluctuating on a monthly time scale and are therefore highly sensitive to the exact timing of the tendering process. In other words, if the tendering documents had been compiled several months earlier or later, the construction cost would have been significantly different. This equally affected all buildings tendered in this volatile time window, and affected all their associated construction costs. CIRS was tendered during this volatile time period and construction date cost impacts are shown in the sensitivity analysis (sensitivity variable

#4). These changing costs were very challenging to the CIRS stakeholders, as escalating costs became a moving target. With CIRS having a fixed budget, this meant that there was a continual pressure to 'value engineer' out key green components. CIRS tendering occurred during a negative escalation year, where prices were beginning to recover. However, the accumulated price increase had not had sufficient time to decline to lower levels. The Stats Canada VCPI shows a price index of 137.4 for the 2nd quarter of 2009, down from a peak of 163.5 in 2008 compared to the 2002 baseline year price index of 100 units.

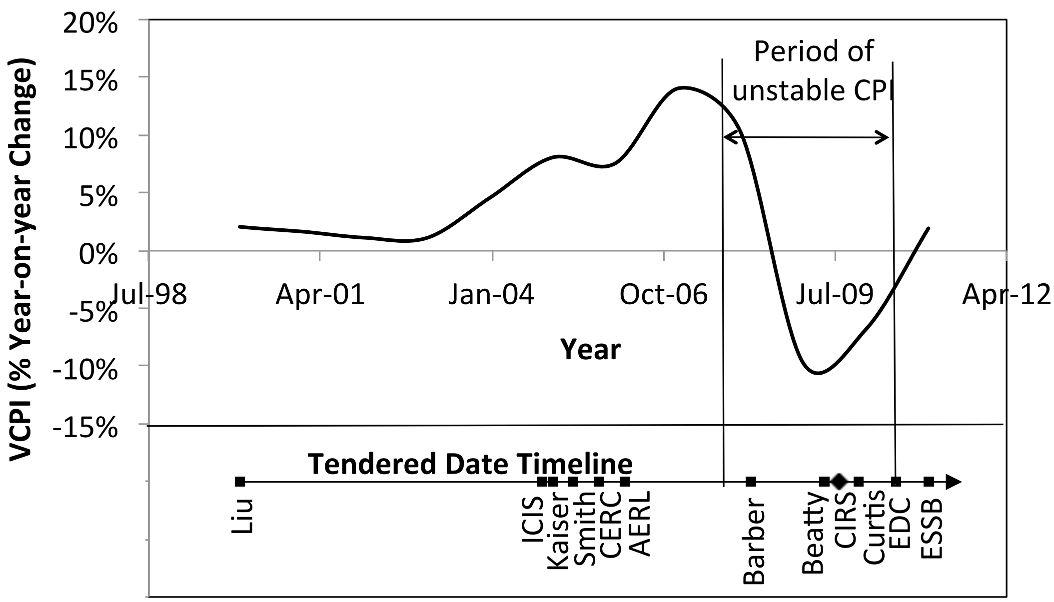

Figure 2.1 Construction Price Index for Vancouver as shown with respect to reported year. The tendered timeline indicates the final approved cost and date (Source: UBC Board of Governors reports)

2.7 CIRS costs and assumptions

CIRS is designed so that many of the operational expenses could potentially be either greatly reduced or entirely eliminated. The intent of CIRS is that it will not require an external water supply and water treatment services, hence eliminating the annual budget impact to UBC for the provision of potable water or sewage treatment. However, CIRS has experienced additional challenges, and after 18 months of operation, some of the net positive design intents have been difficult to attain — particularly the energy and water design goals. Overcoming these difficulties is part of the learning process for the CIRS project.

Energy: CIRS's four energy supply solutions (heat recovery, solar PV, geoexchange and solar thermal hot water), along with expected demand were modelled by Stantec Consulting Inc, and a BC Hydro sponsored energy model. This included expected usage, scheduling and climate adjusted demand simulation in eQuest. Unit energy costs were derived from BC Hydro electrical costs,which, in comparison to natural gas price, are relatively stable. As mentioned, CIRS is attempting to achieve net-positive performance in terms of operational carbon and energy. The design goal is that adding the CIRS building to the UBC campus will reduce UBC's overall energy and carbon use. The intent is that the building should require less total energy input than it returns to a neighbouring building in the form of thermal energy, thus reducing campus steam consumption and associated carbon emissions. This is to be achieved by recovering waste heat from the fume hood ventilation system of an adjacent laboratory building , Earth and Ocean Sciences (E&OS), to fulfill CIRS's own incremental space-heating requirement (which Stantec Consulting modelled at 306 MWh/yr) and return the excess 600 MWhr/yr of energy back to the University). This strategy was to theoretically reduce natural gas consumption at the UBC steam plant by 860 MWh/yr (as modelled). If achieved, this reduction in campus natural gas consumption will be greater than the total amount of electricity purchased from the electric utility for CIRS (modelled at 560 MWh). Additionally, as part of an integrated water-to-water hydronic heat pump system, CIRS is fitted with a geo-exchange loop sized to provide 100% of the CIRS Auditorium cooling load by heat rejection into the ground during the summer. Stored summer heat complements space heating for the building during the winter months. Also, the geo-exchange system serves as back-up in case the heat recovery system on the E&OS building is off-line for repairs or maintenance purposes. Complementing the water-based heating systems of CIRS is a 40 kW solar hot water system capable of meeting about 60% of the hot water needs of the building. However, while the solar PV system and geoexchange systems are functioning correctly, the heat recovery system with E&OS remains problematic. While CIRS is operating better than the UBC average for LEED office buildings, as of December 2013, the building has not yet attained energy positive. These challenges provide a further complication of the LCC modelling process, and provide an opportunity to model the cost of the delay to implement these intents.

Water treatment: CIRS is attempting to achieve net positive performance in water quality. The long-term goal is that CIRS will be 100% dependent on rainwater, all of which is treated on-site. When the water treatment plant is operational, CIRS will also import sewage from neighbouring buildings, as its treatment capacity exceeds building sewage generation. As of December 2013, the water treatment plant is still being implemented and is only partially functional.

Maintenance: Capital renewal expenses will also be reduced relative to a conventional building. The CIRS design in general relies less on active systems and more on passive systems, which fail less frequently and need less maintenance. For example, the west wall of the building employs a green deciduous shading system, whereby natural vegetation provides shade during the summer months and permits solar gains in the winter months after the leaves fall. This means that complicated mechanically-actuated shading systems are avoided. Additionally, major overhauls of large-scale building systems, such as the HVAC ducting, are predicted to be less expensive to replace due to the modular design of the building interior. Academic upgrades are also likely to be less expensive for CIRS, because the design team followed the principles of adaptive design (Arge 2005). The cost of periodic academic upgrades is reduced because the building has reconfigurable interior spaces, which means that upgrades such as office or laboratory improvements do not require invasive retrofit and reconstruction procedures. The maintenance costs for water processing, geo-exchange water heating, solar thermal water pre-heat and PV systems are based on estimates by Corix Utilities. Deconstruction costs of the CIRS facility will be incrementally less than a conventional or a LEED Gold building. This is due to the demountable design of the structure that will allow easy separation of individual components.

Construction Cost: CIRS hard construction cost has been independently evaluated by Heatherbrae, who were commissioned by UBC Properties Trust to give a detailed breakdown of major building components. These figures have been later confirmed during the tendering process completed in July 2009 and later by documents showing final construction costs. Stantec Consulting quantified soft costs for CIRS in Dec 2009. The Stantec costs were then adjusted so that they were aligned with typical soft costs for a UBC LEED Gold building. Due to complications during the procurement path of CIRS, the design and development of the building has been protracted over a five-year period. The changes include site relocation from a different location in the City of Vancouver which necessitated a redesign of many of the building systems. This produced an abnormally high level of carrying costs ($2.0M), retained risk ($0.25M) and a design fee of $5.9M. Additionally, information technology and audio-visual equipment costs for CIRS are high ($2.9M) because of the intensive media and environmental monitoring systems that are specifically for research purposes. Of these costs listed, $6.02M is retained in our LCC model. The costs have been reduced to normalize the comparison to the UBC baseline data set.

Capital renewal: Reconfigurable walls and removable floor panelling allow renovations to be completed without costly and wasteful invasive procedures. Additionally, the use of hybrid and passive technologies implies that major upgrades to systems such as HVAC are less technically demanding. Total capital renewal costs for CIRS are estimated at 47% lower than LEED Gold over 25 years.

Operational uncertainties:

- Municipal upkeep for measures such as landscaping, garbage collection and recycling are estimated to be reduced by 50% (sensitivity variable #5) on the basis of low-maintenance/low-water landscaping and significantly reduced solid waste.

- As previously discussed, there is quantified uncertainty with regards to LEED Gold energy performance, with standard deviations in excess of 30-40% from energy design goals.
- Due to the adaptable interior structure of CIRS, academic upgrade costs are assumed to be 60% lower (sensitivity variable #6).

Deconstruction: Although many of CIRS components are demountable, there is no data to quantify the percentage of materials recoverable. In particular, many of the wood structural systems are designed for deconstruction, are reusable, and would likely have market value. However, since estimates for deconstruction cost are not available, only a 10% saving over LEED Gold/Conventional buildings deconstruction cost is assumed (sensitivity variable #7). The model was implemented in an Excel spreadsheet which included modules of data from Perkins and Will and UBC Infrastructure Development. Details are in Appendix A.1

2.8 Results and discussion

Results are separated into two broad categories. First, the whole building cost is examined, including first cost and total cost of ownership. Model validity is tested by analysing model sensitivity to all our major assumptions, and their effect on total cost of ownership. Second, the results of the scenario analysis are discussed, which bundles variables to check for system resiliency under three simple energy and carbon tax regimes.

First cost: The first cost of a building is defined as the hard construction costs aggregated with adjusted soft costs, including site and relocation costs, retained risk, furniture, fixtures and equipment (FF&E), UBC information technology and audio-visual (IT/AV) allowance, contingency, consultant fees and permit fees. After matching each line-item cost between each of the eleven buildings in the base-case group and CIRS, the construction and soft cost of each building were projected into 2011 NPV dollars to account for inflation. The cost of CIRS was then compared to this base-case ensemble in 2011 NPV dollars.

2.8.1 First-cost comparison

Error! Reference source not found. shows first cost data for eleven core base case academic and research buildings constructed to LEED Gold/Silver standards at UBC. All these costs are actual costs incurred by UBC, based on UBC Board of Governors data, and then scaled to NPV 2011 dollars. A non-linear regression curve fitted through the data shows a clear trend. Determining the regression curve characteristics is challenging because there are many conflating variables driving building cost, such as building height, function, wall to floor ratio and floor area (Bordass & Leaman 2005; Lowe et al. 2006; Cohen et al. 2001). The buildings in the base-case group are similar in height (four stories), function (predominantly offices), floor to wall ratio (4.6-6.1, compared to the typical range of 2-9). Hendrikson (2008), and others, suggests that either linear or power-law trend is an appropriate model for line fitting (Bourgeois et al. 2005; Hendrickson 1989; Clevenger & Haymaker 2006; J. E. Petersen et al. 2007). UBC Properties Trust (UBCPT) has observed economy-of-scale gains for larger campus buildings, which would show as a power law exponent <1. This trend was observed in the regression model with an exponent of 0.91 and a model fit R^2 correlation coefficient of 0.97. The results of the regression model are shown in **Error! Reference source not found.**.

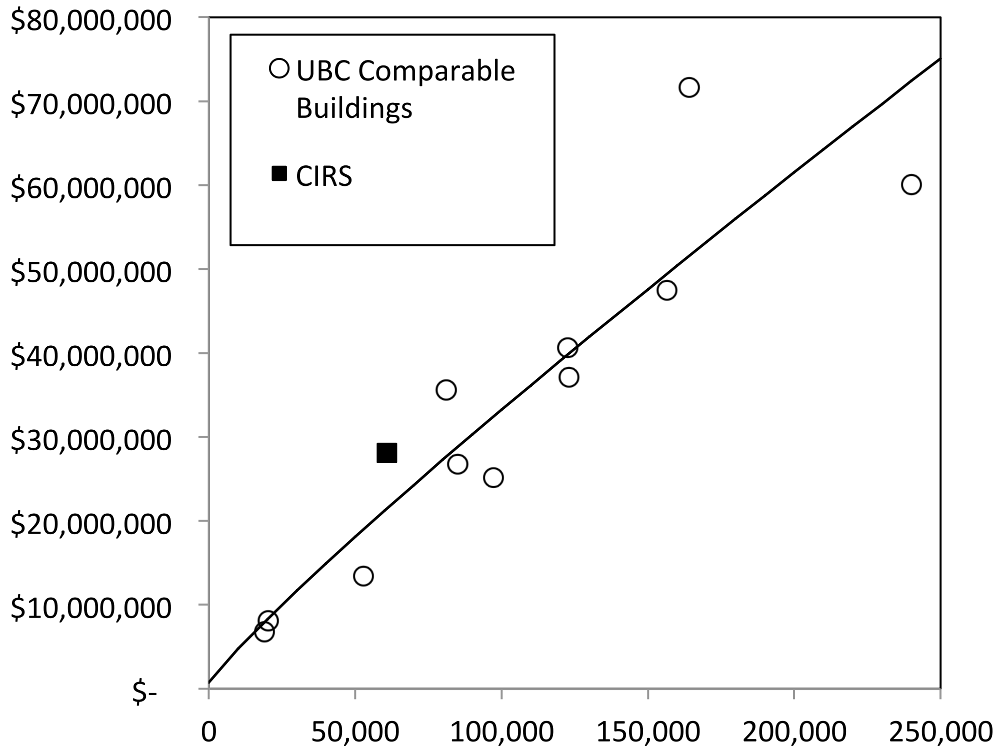

Figure 2.2 UBCPT construction cost data, in $CDN for LEED Gold/Silver equivalent buildings. Standard deviation which shows the variation of data from the central tendency, is indicated by curves above and below the best curve fit. The cross over point at the y axis is $0.72 million.

The unit area cost of CIRS is $411 per sq.ft (2011 dollars) whereas the group mean of comparison buildings was $315 meaning that CIRS is 28% higher than the mean (or $125 over the mean). CIRS' cost is within two standard deviation range of variation (Figure 2.3). Therefore, within 95% of data variability, the CIRS cost was within the expected cost range for UBC buildings based on the level of cost analysis. In other words, the cost of CIRS does not vary significantly from those of other UBC buildings built to the current minimum building standard at UBC.

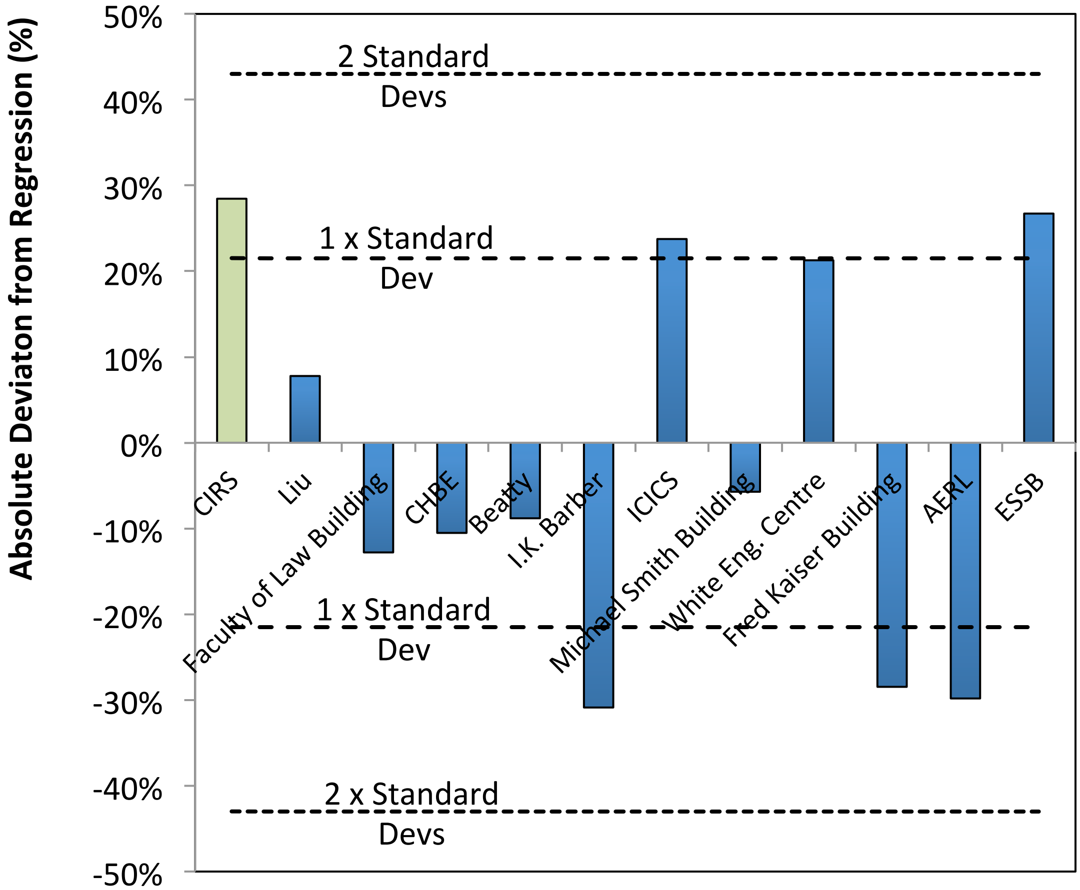

Figure 2.3 Deviation from the regression line for the comparison set of buildings.
A building hypothetically exactly on the line would have 0% deviation from the mean. Statistically, one standard deviation captures 68.3% of the variability around the mean. Similarly, two standard deviations encompass about 95.4% of the variability around the mean.

The incremental budget increase over the base-case (28%) has been a central point of discussion within the CIRS design team. Many of the costs cannot be directly attributable to building to the UBC 'regenerative' standard, per se, but rather due to a multitude of factors. These include:

a. The high ceiling to floor ratio, which lowers the effective unit area per building volume. Ground floor rooms in CIRS have ceiling heights in excess of 4 m, which is higher than in most buildings in the base-case group of buildings.

b. The façade to floor ratio is higher than in baseline buildings. The courtyard and 'U'-shaped design increases daylighting, but also increase construction costs.

c. The technical challenge of building one of the first four-storey wooden structures in BC. Commercial timber-framed structures on the scale of CIRS have only just been approved by the BC building code. For CIRS, the cost premium for wood is estimated to be in the range of $0.5-0.75M, although this premium is expected to decline for future buildings as wood construction knowledge becomes more established.

Further cost premium are buried in the extensive integration of building systems. With CIRS' features have more than one budget impact, such as the green roof requiring both an advanced supporting envelope and an incrementally stronger supporting structural element, the cost are distributed across numerous line-items. This is a general challenge to costing highly integrated systems and requires further research.

It is perhaps worth noting that the cost of CIRS is competitive with other advanced buildings in the Pacific Northwest. For comparison, Cascadia reports that Living Building construction premiums over conventional buildings are 24-49% for office buildings (CaGBC 2008). However, these are modelled costs, not actual as-built costs. The only regional buildings built to the same regenerative principles are the 20,000 ft^2 Vandusen Botanical Garden Visitor Centre, Vancouver, (67% over UBC LEED baseline) and the 52,000 ft^2 Bullitt Foundation building, Seattle (42% over UBC LEED baseline). However, differences in building function, shape complexity and location mean that direct comparisons should be viewed with caution. A rigourous comparison would require detailed cost harmonization (to account for differences in soft cost accounting), along with appropriate regional construction cost corrections.

2.9 Total cost of ownership

Total cost of ownership (TOC) represents the total budget impact to UBC over the service life of the building, including first cost, operational costs, capital renewal costs and deconstruction costs. For the discount rate, the BC Government nominal rate of 7.1% is used (real discount rate of 5.0%). Escalation rates are set at the Canada consumer price index of 2.1%, with minor variations on individual line items for locally high escalation rates. Operational costs include utility costs (electrical, natural gas, carbon offsets and carbon tax) and maintenance cost (scheduled and unscheduled), general municipal expenses (landscaping, roads) and custodial services (janitorial):

- Capital renewal costs include renewal costs (HVAC, plumbing, fire protection, code upgrades, interior, roofing and enclosure) along with periodic academic upgrades such as replacement of audio-visual and information and technology systems.

- Deconstruction costs at end-of-life include demounting, recycling and demolition. There is considerable uncertainty with regards to the deconstruction cost; however discounting cost over long time periods, even at low discount rates, makes this cost relatively insignificant. The total discounted cost for deconstruction in the year 2061 has a 2011 NPV of only $20-40K, and all further calculations are suppressed for clarity (see sensitivity results).

The results, shown later in Figure 2.4 , indicate that the total cost of ownership difference for LEED Gold versus CIRS declines with time. By year 20.5, the total cost of CIRS drops below the UBC base-case. By year 50, CIRS is $2.0M under the base-case curve. Model error accumulates over long periods of time hence these long-term results should be interpreted with caution.

The operational efficiency of CIRS, which enables CIRS to be less expensive than the LEED Gold basecase, is a composite effect of two main factors:

i) Operation and maintenance (O&M): Cost efficiency becomes apparent when examining aggregated periodic expenses. For example, CIRS' high performance envelope ($R_{walls} = 20$, $R_{roof} = 40$) and 100% day-lighting for occupied floor space, reduce heating and lighting requirements. The energy intensity, when optimised for the building (including lighting and plug loads) , is designed to be ~83kWh/m^2/yr for the basic building.

ii) The CIRS design goal included a heat recovery and return with E&OS. When the system is fully functioning, heat is recovered by CIRS from E&OS by means of a ventilation heat recovery system. The recovered thermal energy will then used to heat the CIRS and rejected heat will be used to pre-heat the air at the E&OS air handling unit air intakes thus reducing this building's steam (and thus natural gas) requirements. This recovery system, when operational, means that CIRS will not require any additional thermal input to satisfy its space heating needs, and will return useful heat back to E&OS and causes a reduction in natural gas use and GHG emissions at UBC. However, this will cause an increase in electricity consumption to run the heat exchanger pumps and adds 23kWh/m^2/yr to the modelled 83kWh/m^2/yr electrical load..

Unfortunately, the current operational performance of CIRS has still yet to be realized. Figure 2.4 shows that, even after 24 months of operation, the energy consumption of CIRS is missing the design goal. CIRS data is from a review study (Fedoruk 2013). While CIRS' energy performance is below the UBC benchmark for typical office buildings, it is far above the original Stantec energy model.

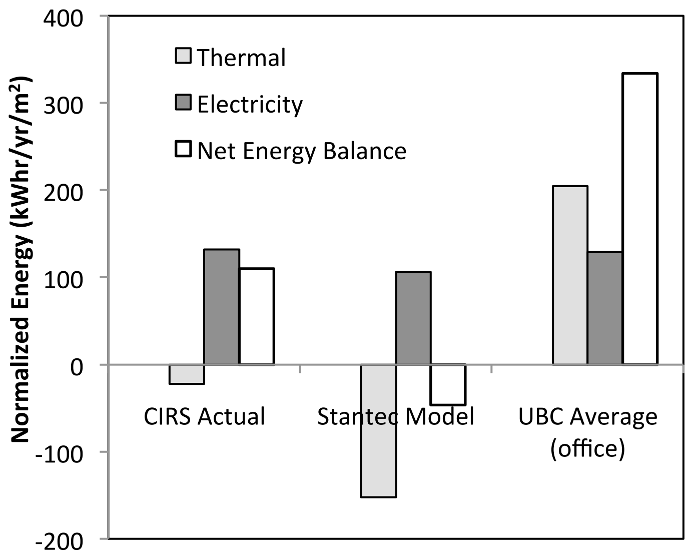

Figure 2.4: Actual performance versus modelled cost for CIRS (December 2011 to December 2012). UBC office building average performance is shown for comparison.

In summary, if CIRS was operating to the design intent, savings due to carbon tax and energy reductions, along with reduced maintenance costs, could be worth as much as $3.3 million (2011 dollars) over 25 years. Unfortunately, if the actual building performance remains non-optimized, and continues running as metered over the last 24 months, the cost savings will be closer to a lower value of $2.6 million (2011 dollars), leading to a payback period increase of 4 years from 22 to 26 years.

2.9.1 Sensitivity analysis

The model is tested using sensitivity analysis, as recommended by NIST and ISO 15686-5, to check the significance of variations with respect to the most uncertain variables (sensitivity variables 1 through 7). Each assumption is analysed to check for their influence on the total cost of ownership (see Table 2.2). Each variable is subjected to a cost increase of 10% and an NPV cost is calculated for each item as suggested by NIST. The cost increase is then presented as a percentage of the total cost of ownership.

Table 2.2 Results of sensitivity analysis.
The cost difference for an incremental increase of 10% for each variable is calculated in NPV (2011 dollars) and % of total cost of ownership (TOC).

Cost Assumptions	**Life Phase**	**Change in Base-case LEED 25 Yr LCC**		**Change in CIRS 25Yr LCC**	
		in PV (2011 dollars)	in % of TOC	in PV (2011 dollars)	in % of TOC
1. Energy cost (+10%)	Operation (25 years)	$174,100	0.4%	$19,200	0.04%
2. O&M costs (+10%)	Operation (25 years)	$1,001,000	2.4%	$708,000	1.7%
3. First Cost Premium (+10%)	Construction	$2,107,600	5.0%	$2,858,000	6.9%
4. Construction Escalation (CIRS tender +5months)	Construction	-	-	$830,000	2.0%
5. Municipal upkeep (CIRS standard)	Operation (25 years)	$5,600	0.01%	$2,800	0.01%
6. Adaptable features savings (CIRS standard)	Operation (25 years)	-	-	$166,900	0.4%
7.Deconstruction cost (+10%)	Demolition (50th year)	$6,300	0.02%	$6,300	0.02%

The sensitivity analysis shows that a cost perturbation will have different effects according to exactly when they impact the building's life-cycle. Due to discounting, costs that occur later in building life have less impact than earlier or at construction.

2.9.2 Summary of sensitivity analysis

- The LEED base-case model is more sensitive to changes in energy cost. The budget impact for a 10% initial step increase in energy cost would cost ~$174k, considerably higher than the CIRS case. The impact to CIRS energy budget is small, in part because CIRS's supply-side technologies are more valuable if external energy costs increase.

- A 10% O&M cost increase, propagating for 25 years, has cost impacts of 2.4% and 1.7%, for the base-case and CIRS, respectively. The LEED base-case is slightly higher due to more intensive routine maintenance requirements.
- A 10% perturbation of construction cost yields a more significant 5.0% and 6.9% changes in the total cost of ownership (TOC) for LEED and CIRS, respectively. This shows that changes in first cost drive the TOC for both building types. While operating and capital renewal costs dominate the undiscounted total cost of ownership, the discount rate disproportionally weights the first cost.
- The tendering date for the CIRS construction cost is sensitive to the exact date of submission. If the building had been built only 5 months later, UBC would have benefited by $830K in savings. It is worth noting that the tendering date is not a single point (except by convention), so it is arbitrary to assign all the costs to that tendering date. As the sensitivity analysis shows, if the cost estimates had been applied at slightly different tendering date, the calculated NPV of CIRS, and several other buildings, would have been different. For CIRS, +5 months would have resulted in a 2% decrease of TOC and 3% of the construction cost. This uncertainty is a direct result of the high volatility of the CPI, fortunately a relatively rare event. The uncertainty affects all buildings built during the same volatile period. In this case, the shift affects the model base-case and CIRS equally.

An additional sensitivity analysis was completed for different discount rates. Figure 2.5 shows the effect of discounting for a social rate (3% real) versus market rate (5% real). Break-even is 2.2 years sooner for the lower rate. More marked is the difference in TOC at 50 years; the savings by CIRS is $8.4M for the 3% social discount rate and $3.2M for the 5% market rate.

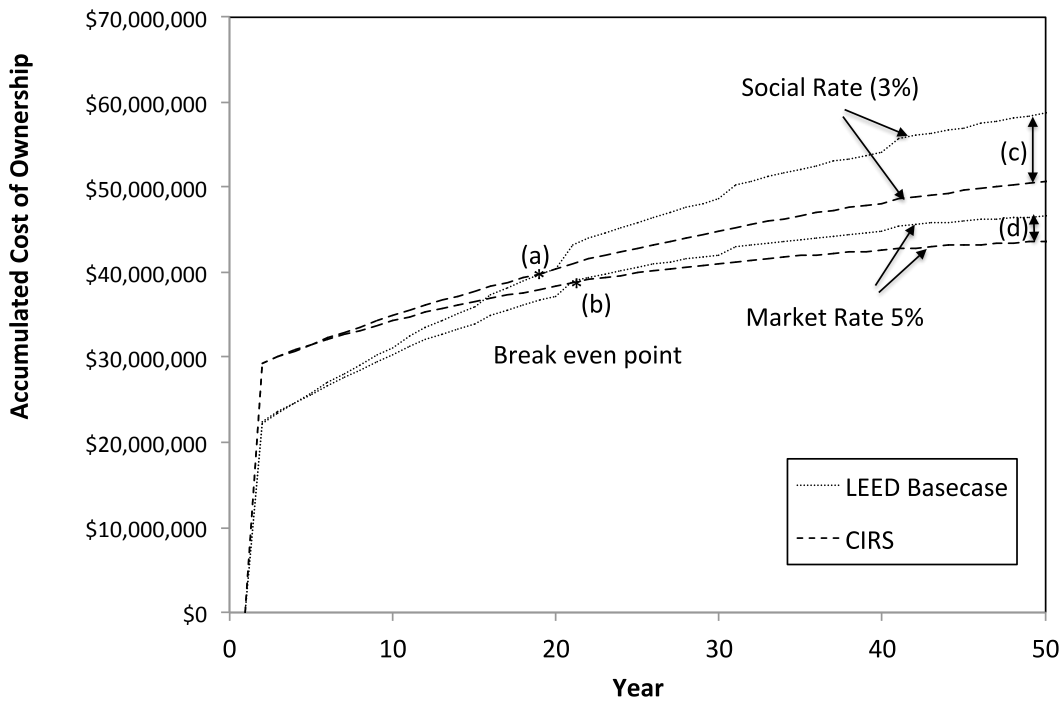

Figure 2.5 : Accumulated cost of ownership in 2011 dollars.
The breakeven points are shown for (a) 3% real discount rate and (b) 5% real discount rate. The breakeven point is reduced by 2.2 years for the lower rate. At 50 years, the relative TOC differential is shown for (c) $8.4M and (d) $3.2M in 2011 dollars.

The relationship between discount rate and break-even time is shown in Figure 2.6. The break-even time is particularly sensitive to higher rates, as expected. Rates above 7.2% result in break-even not being reached within 50 years. A declining discount rate was calculated, for a linear decline from 5-2% over 50 years. This produced break-even at

20.5 years, not markedly different from the break-even for discount rates of 3% and 5% (not shown in plot). This is because most of the value attrition has occurred early in life; savings occurring later in life, though more than the social discount rate, are not contributing sufficiently to the TOC.

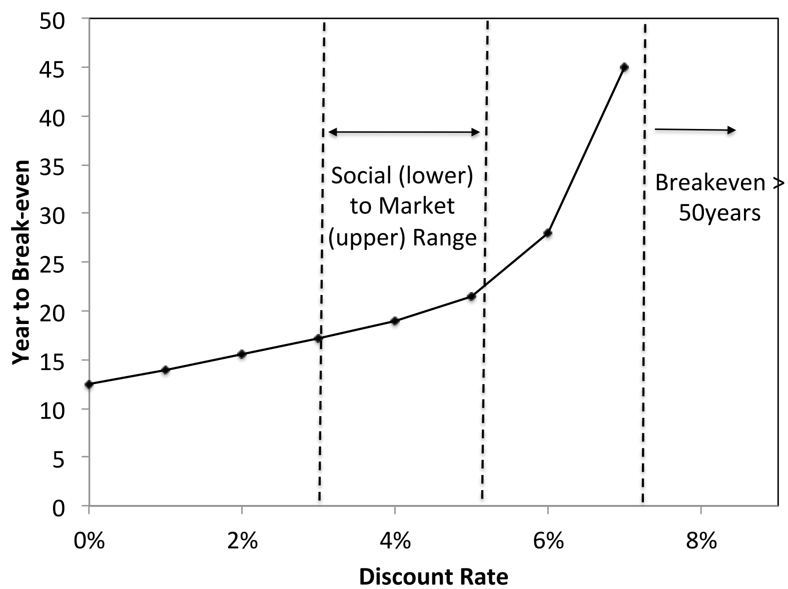

Figure 2.6 Breakeven curve for an increasing discount rate.
Typical rates are bounded between 3-5.2%. Rates greater than 7.2% means that break-even is never attained (LEED base-case has lower TOC for t < 50years)

In summary, the sensitivity analysis for discounting clearly shows that, for a future where discount rates are high, front loaded costs remain dominant. In terms of policy, the financial model for regenerative buildings needs to consider the institutional approach to the future-value of money. The sensitivity shows that there is a case for social discount rates (as discussed in section 2.4.1), which may be justifiable for public buildings that have high social utility.

2.10 Scenario analysis

The stakeholders, particularly the UBC University Sustainability Initiative and UBC Infrastructure Development, are particularly interested in the energy cost for CIRS. UBC campus has specific supply constraints, both in terms of transmission of electricity supply from Vancouver and GHG constraints from natural gas consumption. Options for low demand are particularly attractive, which the regenerative standard for CIRS attempts to pioneer. Simply extrapolating the cost of utilities from average historical values is limited because the results do not reflect the variation of inflation over time. Scenario analysis is used to model a small subset of feasible step changes in cost. The goal of CIRS' demand side management is to reduce energy consumption over time. Here, a conservative estimate is taken which assumes the worst-case eventuality that demand will not increase significantly over time.

In order to test the performance of the building with respect to sudden fluctuations in energy price and taxation, three simple what-if scenarios are used to check for financial resilience to utility price increases. The relevant variables bundled for both scenarios are natural gas price (for steam generation), electricity price (for heat-pumps, PV system, HVAC and lighting) and carbon taxation (on natural gas). The results of three scenarios, including a current trends future, are shown in Figure 2.7. The current trend is the actual performance figures for the first year of operation (2012-2013). In the current-trend case, we assume that there are no changes for the next 25 years and no attempts to improve standards up to the high performance design model.

- In the first scenario, building energy systems are re-commissioned and raised to the original net energy positive design intent. Additionally, the price of natural gas jumps 25% in year 5, 15% in year 10, then remains elevated for the balance of 25 years while continuing to escalate at the Consumer Price Index (CPI) rate. Also, the escalation rate for electricity is 0.5% above Canada CPI rate, with no initial jump. This scenario represents an 'expensive' future for utilities, but no change in current carbon regulation. The jumps in natural gas reflect historical volatility in the North American natural gas market. The scenario results show that the base-case becomes more expensive, while CIRS has stronger revenue generation. The difference in performance becomes larger in the 'expensive' future.
- In the second scenario, once again, building energy systems are re-commissioned and raised to the design intent. Natural gas prices fall by 10% in year 10 and carbon taxation increases 5.5% annually. This scenario represents a heavily taxed carbon future resulting in natural gas prices being driven down due to demand reduction. The increased tax penalizes natural gas consumption more than electricity (due to British Columbia's low emission factor for hydro electrical power). This means that CIRS 'revenue' increases while the LEED base-case becomes more expensive.
- In the third scenario, again, the building is renovated to the intended design standard. Carbon taxation and offsetting are removed in year 10 due to political changes and the thermal source (E&OS building) is demolished in 10 years. CIRS' source of heat-recovered energy is removed and the building requires a

conventional supply of thermal heating. This future represents a return to the past, with no carbon tax, nor energy recovery opportunities. In this future CIRS is never energy positive but still outperforms the base-case LEED building, though by a much smaller margin. Note that electricity consumption is reduced slightly because the E&OS heat pumps are not required.

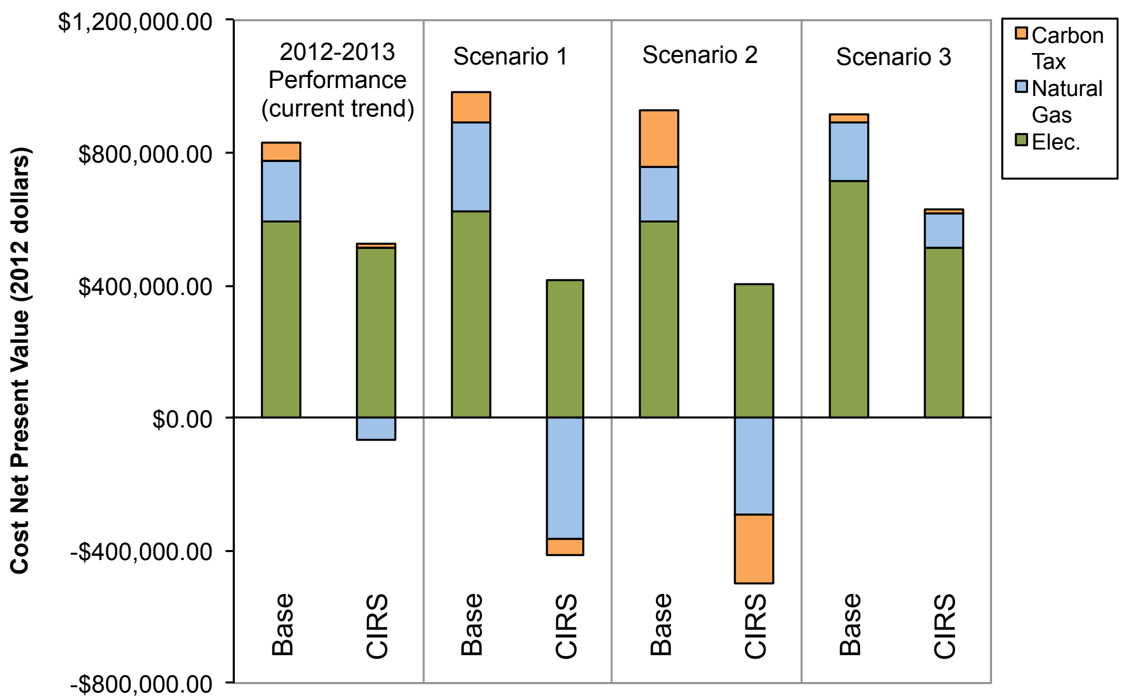

Figure 2.7 CIRS 25year NPV cost (2010 dollars) of electricity, natural gas and carbon tax compared to a LEED Gold base case.
Scenario 1: Price of natural gas jumps 25% in year 5, 15% in year 10, electricity rises 0.5% over CPI; Scenario 2, Natural gas prices fall by 10% in year 10 and carbon taxation increases 5.5% annually; Scenario 3: Carbon tax is removed in year 10 and heat recovery from building terminated after 10 years.

2.11 Life-cycle costing as a learning process

While the results of the model are important in terms of verification, and tracking progress, the process of building the LCC was found to be useful as a catalyst to facilitate stakeholder collaboration. The modelling procedure, as a process, allowed participants to better understand the relationship between costs incurred at different life phases. Building the model became a learning process of knowledge co-generation between participating stakeholders. Groups representing both first cost control and operational cost management were engaged at various times during the modelling process which spanned two years of work. Unfortunately, the LCC study was engaged too late in the design phase to have a direct impact on the IDP. Nonetheless, the level of participation in the study was broad and the 'lessons learnt' enable a road-map to be drawn for future model construction. Figure 2.8 shows a suggested process structure that is potentially generalizable to any larger institution.

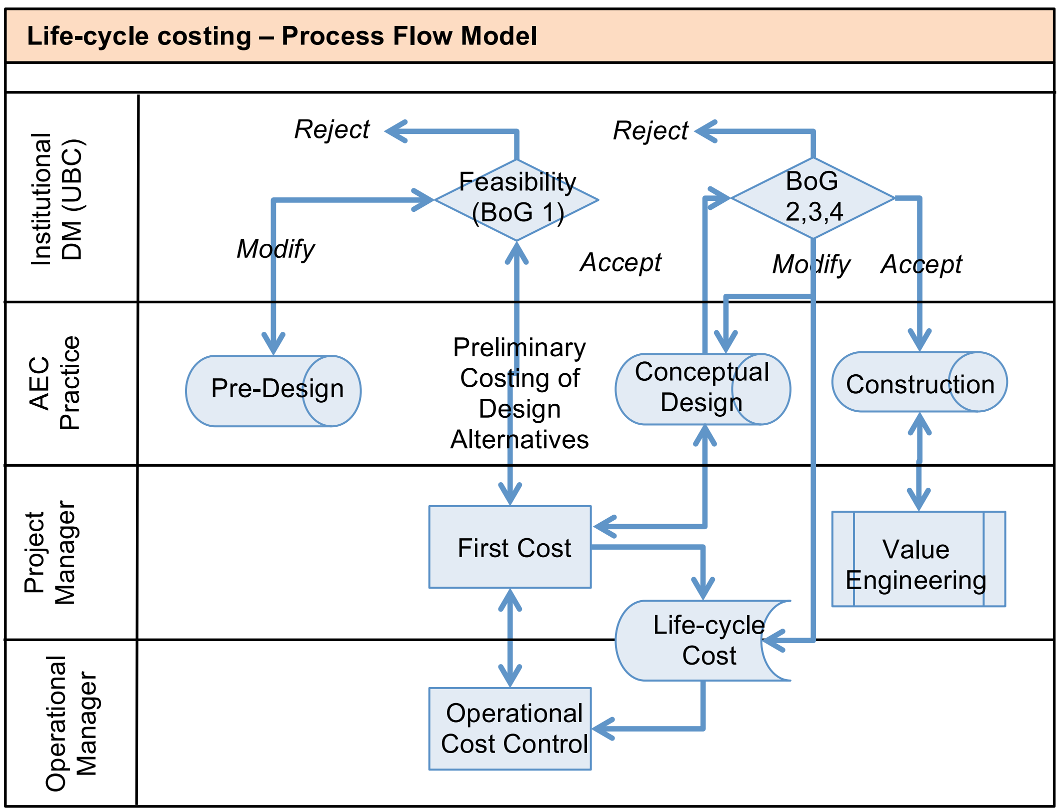

Figure 2.8 Flow diagram showing process and relationship between building stakeholders. Stakeholders are architecture, engineer and construction (AEC) professionals; project manager and operations management. The institutional decision-makers (DM) at UBC is predominately led by the Board of Governors (BoG). The University Sustainability Initiative (USI) continues to provide considerable facilitation and leadership with sustainability projects.

For high intensity buildings, if operational costs are significant for feasibility and conceptual design, such as for aquatic centres, they can be part of a conventional approach. Froese suggests, that for conventional buildings, operational costs are less significant for feasibility, but become significant in conceptual and preliminary design and can influence design decision-making (personal communication, 2014). In contrast, the data recovered from UBC BoG records show that participation from operations is limited and the entire bottom row of Figure 2.8 is usually not represented. Without operational input and expertise present at the decision table, a life cycle model is much more challenging to construct. The lack of input means that downstream savings will likely remain invisible, a net loss to the operational budget. Fedoruk (2013) also finds that the gap between design and performance has been persistent and similarly urges better integration between design and operation.

2.12 Conclusions

The modelled results challenge the conventional preconception that high performance buildings, such as CIRS, always 'cost more'. Results show that the overall outcome is complicated by variations in first cost, the difficulty in pinpointing long-term costs and the challenges of getting a building operating to intended performance. The construction cost premium of CIRS is 28% more than a statistical base-case regression average, but that this value is within two standard deviation of cost variation for comparable LEED campus buildings. This means that CIRS is within the 95% probability of expected costs as defined by the base-group variation. Whereas the building is within an accepted band of statistical variation, the question about whether a particular premium against a modelled base case is justifiable must then be determined by stakeholders when weighing the premium against long-term discounted savings. Unfortunately, this cost is profoundly affected by a host of long-term assumptions and exogenous variability. While life-cycle costs show that operational and capital renewal savings for CIRS enable a possible break-even with the base-case building at 20.5 years of operation, this period would be extended by four years if initial building operational problems are not resolved. Although recouping an initial incremental investment is within reach for owner-operator institutions, the period of time required will be protracted if there is insufficient institutional support to continuously maintain, monitor and re-commission buildings to ensure installed systems can reach their full operating potential.

Furthermore, escalation rates, along with discount rates, mean that the break-even point is highly sensitive to discount rates. The use of a social discount rate instead of a market rate results in a 2.2 year shortening of investment pay-back time. Conversely, real rates above 7.2% result in a first-cost investment never paying off. Although such a high rate is rare, institutions would do well to check the upper bound for payoff in their LCC models, since even moderate discount rates may delay break-even to an unacceptably long period of time.

Little is known about the uncertainty for operational costs over long time spans; however, market discount rates extinguish long-term financial impacts, rendering uncertainty less relevant in terms of Net Present Value. Mathematical methods for handling ‘unknown unknowns’ are beyond the scope of the model. These types are associated with large unexpected capital renewal costs, or unusual repair and maintenance issues. In the absence of this cost data, a great deal of caution must be taken when interpreting the results. This motivates the use of scenario analysis to explore feasible futures, which is of utility to decision-makers when they are comparing performance options at the design stage. Our model, like all LCC models, is constructed to *compare* options only. The absolute real world costs will likely be divergent from modelled costs.

The scenario analysis results for plausible energy futures at UBC show that CIRS is resilient with respect to feasible step-wise changes in the price of electricity, natural gas and carbon tax. However, this resiliency can only be fully realized if the building performs up to the intended design standard. Once this is attained, the CIRS regenerative design approach is more likely to show proof-of-principle with regards to 'future-proofing' operation.

While the model results are useful for strategic planning when designing regenerative buildings, the model *process* also has high institutional value. The utility of LCC models, therefore, is not in the actual numbers that are produced by the model. Rather, it is in the collaborative process of modelling, which requires considerable cooperation in terms of acquiring data to structure costs, identifying assumptions, and describing unknown uncertainties to discover risk that may otherwise have been overlooked. This is particularly pertinent for complex building projects that, like regenerative buildings, are pushing the edge of attainability for advanced buildings.

Chapter 3: Life-cycle Assessment for High Performance Buildings: Comparing ICT, Furniture and Structural Impacts for LEED and Regenerative Buildings

3.1 Summary

A whole-building case-study life-cycle environmental analysis is conducted of CIRS, an advanced 'regenerative' beyond-best practices building which is compared against a similar LEED Gold building. The building attempts to reduce environmental burdens by strategies such as the use of structural wood to store carbon, and attempts to reduce material impacts by low-impact information technologies and adaptable furnishings and fixtures. In order to gauge how well CIRS is reaching net-positive environmental targets, from a material's point of view, a case-study is undertaken to compare embodied performance against a similar best-practice LEED Gold building and UBC benchmarks. The study integrates Global Warming Potential (GWP) embodied impacts from three separate studies, building structure data from the UBC-LCA database, furniture systems data from Haworth Inc. and information computing technologies data from a UBC IT study. The combined GWP results show that, particularly over the long term, interior systems with high churn (replacement) rates aggregate significant impacts over decadal periods of time. This is in contrast to the building structure, which incurs a single large embodied impact at construction and then slowly aggregates recurring impacts during building life. The GWP embodied impacts of devices and building components are found to scale linearly with their mass. The ICT coefficient is 27 kg CO2-eq per kg, for furniture systems it is 1.3 kg CO2-eq per kg, and for structural systems it is ~0.2 kg CO2-

eq per kg. This assessment opens possibilities for simple benchmarking and an informative heuristic at the design stage for new buildings. The study also shows the importance of continuous assessment for embodied performance, because of rapid turn-over of interior systems, where interventions at each innovation cycle can lower impacts.

3.2 Supporting participation and acknowledgment statement

Data and modelling contributions: Haworth Inc, UBC Information Technology, Rob Sianchuk (Instructor, UBC), Max Richter (Perkins + Will Architects)

Decision stakeholders: UBC Information Technology, UBC University Sustainability Initiative

Co-authors: Paul Teehan (PhD Candidate, IRES, UBC), Rob Sianchuk (Instructor, UBC)

Mentorship: UBC LCA Alliance

3.3 Introduction

The imperative for the use of life-cycle assessment for advancing an environmentally responsible economy for Canada has been identified by the recently dismantled National Round Table on the Environment and the Economy (NRTEE 2012). The development of life-cycle analysis to evaluate the environmental performance of buildings has been progressing since the early1990s. This has been motivated by a recognition of the extensive impacts of buildings on the global environment and a need to meet the market demand for measured and verifiable environmental performance information. There is the additional need to shift from single performance measures, such as CO2 or energy performance, to a more comprehensive set of environmental metrics (ISO 2010).

Determining environmental impacts for buildings is also becoming a broad requirement of building assessment systems and standards across North America. This includes codes such as the 2010 California Green Building Standards Code, the 2012 International Green Construction Code from the International Code Council (section 303), LEED v4, and standards such as ANSI/GBI 01-2010, and ANSI/ASHRAE/USGBC/IES Standard 189.1-2011. These formal assessment approaches are critical to encouraging transparency, and to assisting improvement at all stages in a building's life-cycle. In particular, the need to track progress against benchmarks is being regarded as critical to attaining high performance targets. With performance problems being reported for 'green' buildings, there is a need to match follow-up design claims with post-occupancy quality assurance against best-practices benchmarks (Dixit et al. 2012) (Lstiburek 2008).

Benchmarking building design requires consistency in methodology and calculation on product flows and process activities that occur during the product manufacture, construction-installation, use and end-of-life-cycle stages of a building life-cycle. Benchmarking also requires consistency in methodology and reliable data for construction and use, along with detailed and publicly available life-cycle inventories of materials. Models should be explicit, transparent and consistent in terms of methodology and calculation (König & De Cristofaro 2012; Wittstock et al. 2011). However, benchmarking for LCA is more challenging, due to regional, model structure and database differences (Dixit et al. 2012). The current efforts for benchmarking are fragmented. In North America, LEED v4 is likely to be offering a simplified version of LCA for competing designs, where the USGBC are suggesting the use of a reference design approach (NC-v4 MRc1 Building life-cycle impact reduction - Option 4). However, no benchmarking approach has yet to be used other than examining different design options. Additional work for life-cycle benchmarks of the Canadian residential building stock has been completed (Bowick 2011). However, very little benchmark work has been completed for the cradle-to-gate impacts of commercial buildings, nor for buildings built to various standards of performance or various claims of 'green' outcomes. An additional need for research is on the study of impacts attributable to non-fixed inventories within buildings. These include high-churn items which have frequent replacement cycles, such as office furniture or computing technologies. These systems, which include furniture, fixtures and finishes, can represent a significant proportion of total impact (Fay & Treloar 1998). Comparing these impacts against other building related impacts is useful from a methodological standpoint for investigating whether, (1) reduction of environmental impacts can be attained at minimum cost, (2) improvements can be measured against a benchmark, and (3) environmentally beneficial decision-making can occur on a continuous basis.

3.3.1 Study goal and scope

This study examines the embodied environmental impact of high performance building structures, and compares this to the relative embodied impacts of select indoor systems, furniture, fixtures and information and computing technologies (ICT). Two case-study buildings, representing two distinct standards claiming status as 'high performance' are examined: the Aquatic Environment Research Laboratory (LEED Gold standard) and the

Centre for Interactive Research in Sustainability (‘regenerative’ standard; has achieved LEED Platinum status).

The aspirational goal of LEED is to incrementally improve performance over conventional standards. The aspirational goal of ‘regenerative’ design is to go beyond reducing impacts to producing net gains (Plessis 2012; Cole et al. 2013). The embodied impacts of the non-fixed inventories in the case-study buildings are compared to structural impact data from the UBC-LCA database. The study does not include operational energy impacts (these are reported in Chapter 4). Of particular interest in the study are the relative churn rates of different technologies. High churn rate technologies may have small impacts for each replacement, but aggregate over longer times scales to compete with larger but slower scale churn rates.

The overall novelty of the research is that the benchmarking and comparison of impacts at a systems’ level reveals broader impact trends in owning and operating buildings. The relatively low impact interior systems may be more, or less, significant than the current industry focus on choice of building materials such as wood or concrete. This is of interest for institutional owners who have influence over supply management, technological purchase decisions, and at least partial control of operational replacement schedules.

3.4 Methodology

The LCA study presented in this paper is an integrated model of three separate LCA analyses – a structural LCA of the CIRS building, and two LCA studies of the interior systems of the building. The data embedded in the integrated model is a contribution of research partners, including data and previous modeling work from UBC Information and Technology, Haworth Inc, UBC Infrastructure Development and UBC University Sustainability Initiative. The system boundary includes all enclosure systems, interior walls, floor structure, roofing elements and window systems, and adheres to ISO 21931-1 except for end-of-life impacts which are not considering in these models due to a lack of data. The two interior system models are based on (a) life-cycle impact data, in particular GWP, from Haworth for furnishings and fixtures and (b) life-cycle impact data from an ICT study for all computer systems and peripherals. Due to data availability, this study does not include HVAC, plumbing, electrical, and associated supporting systems. Energy infrastructure components, such as the PV system, are also not included and are left for future studies.

Several limitations of the furniture system data have constrained this analysis. First, a base case is not presented for furniture systems. In addition, the LCIA data on Haworth furniture systems is restricted to GWP; hence this is the only comparable impact between all three models. The comparison of GWP between the models is therefore the focus of the study.

The analysis is structured in five sections. Firstly, in section 3.4.1 an overview is presented of the case-study buildings that provide a context for the validity of building-to-building comparison. The next three sections, 3.5.1 - 3.5.3, provide an overview of the three models (structural, furniture systems and ICT). The final section, 3.8, is an analysis of the results of the integration of the three models. An important novelty of the study is the analysis of temporal relationships between the models in terms of durability, life span and scale of impact. The results indicate that decision-makers are not only challenged by the need to reduce impact at the time of initial construction, but also by continuous micro-decisions that are required to reduce recurring impacts.

3.4.1 Background on case-study buildings

The two case-study buildings are comparable and similar in terms of overall function, programming, occupancy, floor area and volume. In summary:

- AERL was opened in 2006 and is LEED Gold certified. The superstructure is a concrete building with extensive use of glazing. The AERL building is constructed with minimal finishes and most of the interior surfaces are exposed or polished concrete. The gable ends of the building are clad with non-glazed white brick sourced from Ontario. AERL employs natural stack ventilation and extensive day-lighting via narrow office bars. Every floor has operable windows, rather similar to those in CIRS. The IT systems of AERL are a conventional mixture of desktops, lap-tops and LCD monitors.
- CIRS was opened in 2011 and has received a LEED Platinum rating. However, the primary intent was not a rating by LEED, but to be a regenerative building,

designed with specific aspirational targets that were set during the design process[2]. For the specific case of CIRS, these include:

(1) Returning more energy to the campus community than is consumed via heat exchange with an adjacent building, along with inputs from solar thermal, PV and geo-exchange. The design intent is that the heat exchange design will enable a net positive effect of reductions of carbon emissions for the campus community;

(2) Sequestering more carbon than was emitted during construction, via storage of carbon in a wood structure. CIRS employs the extensive use of wood to increase carbon storage and to displace environmentally intensive materials such as steel and concrete;

(3) Reducing the recurrence of embodied impacts by using passive, smart and adaptable systems. The building employs a thin-client IT mix, supported by a centralized server, to dematerialize and reduce impacts.

CIRS is also synergistic with campus sustainability strategies and is built within local and regional targets, mandates and goals. These include carbon neutrality as an aspirational goal for UBC buildings, compliance with British Columbia's 'Wood First' policy, and a carbon neutral campus by 2050. This study focuses on the embodied impacts in points (2) and (3). The operational impacts are left for future study after CIRS energy systems are recommissioned and fully functional.

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[2] Note that the regenerative paradigm is also about improving human well-being, health and happiness within communities and buildings. However, these social metrics are beyond the scope of this study.

Overall, CIRS and AERL are functionally equivalent. They both have four stories above ground level and at least a partial basement. Classrooms, research laboratories and office spaces occupy the bulk of the floor space in both buildings. While both buildings have atria that vertically reach the full four stories, CIRS has a slightly larger atrium circulation area. Most offices are of open or partially open office design, which means that the number of internal walls is minimized.

Both buildings have large auditoriums, although CIRS is larger, with a 450-seat capacity compared to AERL's 140-seat capacity. The volume-to-floor ratio of CIRS is slightly higher due to large floor-ceiling heights throughout the building. Both CIRS and AERL have less meeting rooms/class areas than the UBC average, indicating a heavier emphasis on office use. CIRS has the larger basement/service area due to the entire sub-grade floor being dedicated to UBC storage. The most significant difference between the buildings is the approach to structural systems; CIRS extensively uses glulam structural beams and modular 2x4 Pine-beetle-kill gang-nailed modular ceiling members, whereas AERL uses a poured concrete slab. The CIRS designers took additional steps to reduce recurring impacts. These include installing a thin-client IT system and adaptable furniture systems. Neither of these approaches was adopted for AERL, which mainly considered the structural design challenge and not operational considerations.

3.4.1.1 UBC-LCA database

Then UBC-LCA benchmark data set contains 31 buildings constructed on UBC campus, all of which have various programming schedules. The data set is constructed from individual Athena EIE model results, constructed from four years of reviewed project work by teams of senior undergraduate students in a Civil Engineering course. Details are available in Appendix B. The benchmark data for this study is extracted from office buildings that are functionally similar to CIRS and AERL. Table 3.1 shows the building characteristics for each case along with a comparison with the UBC office average.

Table 3.1 Building characteristics for AERL and CIRS compared to the UBC average (source: UBC-LCA database).
There are no statistics for average areas, volume or surface area from the UBC benchmark.

Building Statistics	**AERL**	**CIRS**	**AERL %**	**CIRS %**	**UBC Office Average**
Class and Meeting Rooms (m^2)	350	330	7%	6%	13%
Auditoria (m^2)	210	380	4%	7%	7%
Office Space (m^2)	830	910	17%	16%	15%
Circulation Areas/Atria (m^2)	850	1010	17%	18%	27%
Washrooms/showers (m^2)	150	200	3%	4%	3%
Labs and research areas (m^2)	1850	1800	38%	32%	26%
Basement and service areas (m^2)	660	1020	13%	18%	8%
Total Area (m^2)	4900	5650	-	-	-
Total volume (m^3)	21000	26000	-	-	-
Total surface area above grade (m^2)	4900	5800	-	-	-
Building height (m)	16	19	-	-	-
Building volume floor-area ratio (-)	4.3	4.6		-	-

3.5 Background on integrated models: structural, ICT and furniture systems

There have been many studies examining overall structural impacts, although many without a formal approach to impact assessment. Two comprehensive meta-studies (Masanet & Stadel 2013 ; Dixit et al. 2012) identify at least 30 studies covering various life-cycle approaches to embodied energy but with only 14 formally approaching GWP and embodied energy using ISO 2006 guidelines. Fewer consider systems within the building, not necessarily due to omission, but simply because they are outside the system boundary.

Previous studies for whole-building LCA, including interior systems, are split between process-LCA and economic input-output (EIO)[3] LCA. Fay (1998) conducted an LCA of whole-building systems using EIO LCA and found that, for office buildings, interior (non-structural) impacts to be significant over a 40-year time span.. The ratio between the life-cycle structural embodied energy (initial and recurring), the furniture systems (initial and recurring) and the building operational energy[4] was 1.79: 1.24: 1.00. In summary, the significant finding of the study is a large impact contribution attributable to components with high replacement rates.

Few studies have attempted whole building assessment using process-LCA (including furnishings and information technologies) due to the extensive data requirements for building a life-cycle inventory (LCI). Additionally, integrating existing life-cycle impact assessment (LCIA) data, particularly regional impacts, is challenging due to a range of factors including system boundaries, data age and quality, methodology and end-of-life assumptions. For this study, which exclusively uses process-LCA, integration is possible because of the implementation of harmonization steps. End-of-life impacts are removed due to inconsistencies in data. Additionally, functional units are adjusted to the building

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[3] Process LCA is based on detailed physical inventories of a product or process and attributing environmental impacts to material flows. EIO LCA is based on the economic input and output of sector-scale financial interactions and quantifying environmental impacts for each financial flow.
[4] Due to different climate zones, the operational energy cannot be compared to the buildings in this study.

scale, rather than the device or office scale. The first harmonization step is justifiable because end-of-life impacts are found to be small (Junnila 2003)).

The following three sections give an overview of each of the three models in terms of depth, completeness and authorship. Further data is available in Appendix B.

3.5.1 Model 1: Structural systems

Choices for structural systems for commercial buildings have recently become more diversified in the British Columbia building stock. With the proliferation of Glulam and Cross Laminated Timber (CLT) technologies, large-scale wood structures have become feasible. As mentioned, the two case-study buildings represent two distinct approaches to overall structure; CIRS extensively utilizes wood, while AERL is a conventional concrete structure. Structural embodied impacts are well understood in the literature. A large impact is incurred during the initial product fabrication stage and ensuing operational recurring impacts, such renovations, are relatively small and infrequent. For primary energy impacts, a meta study by Sartori et al. shows that 50 years of recurring impacts add 2-11% on top of initial impacts (Sartori & Hestnes 2007). Fay et al. report that recurring embodied energy impacts due to maintenance and refurbishment over 30 years add 32% to overall impacts (Fay & Treloar 1998). Discrepancies are often observed between EIO and process-based LCA, partly because their respective methodologies capture material flows differently. The large difference reported above is too large to be solely attributable to EIO versus process-based LCA which motivates further research, including the work in this chapter.

For this study, structural life-cycle assessment was conducted using the Athena Environmental Impact Estimator (EIE) tool (version 4.0) for the embodied impacts of building components. EIE calculates the potential impact of construction products used to fabricate, transport and assemble building structures. These include building assemblies such as foundations, structural walling, beams, columns, roof assemblies, windows, drywalling, vapor barriers, cladding and insulation. Recurring embodied impacts are included for the upkeep of envelopes and structural elements (e.g. periodic roof replacements). Life-cycle inventory (LCI) data is sourced from the Athena database, which is constructed from surveyed industrial processes, and catalogs of material inputs and outputs in terms of energy, water and materials. Further data is sourced from the UBC-LCA database, which is a comprehensive set of individual Athena EIE studies covering 52% of the academic areas of UBC campus. The models have been built by engineering student teams with oversight by Rob Sianchuk. Information on the building assemblies is sourced from UBC records of structural and architectural drawings and extracted by manual take-offs. For CIRS, the novel structural systems were not easily entered into the limited selection of inputs in Athena EIE. As a check for completeness, and with the assistance of Perkins + Will architects, a bill-of-materials (BoM) confirmation was extracted from the CIRS structural AutoCAD Revit model. The respective bill-of-materials, one from EIE and the other from Revit, were compared against each other with small revisions required for CIRS roofing assembly.

3.5.2 Model 2: Information technologies

The growth of information technology and supporting peripheral devices has become a significant factor in the environmental impacts of office buildings. The absolute impact has been difficult to model; previous work has shown that there are large inconsistencies between various LCA IT studies (Teehan & Kandlikar 2012; Hopkinson & James 2011). This is partly due to the inherent complexities of rapidly changing electronic products, changes over time in ICT efficiency in manufacturing and the types of product use. However, LCA studies have converged in finding that the bulk of environmental impacts is to be found in the production and operational phases whereas, similarly to building structure impacts, transportation and end-of-life impacts are minimal. Currently there is an effort to standardize approaches to LCA for ICT in development with ETSI - European Telecommunications Standards Institute (ETSI) (Andrae 2011).

The CIRS ICT life-cycle assessment was conducted in 2011 using a custom model developed to assist UBC ICT and CIRS stakeholders in selecting a cost-effective and environmentally efficient mix of ICT technologies. Further details on data sources are found in Appendix B . A linear relationship was identified between product mass and embodied CO2, of the order of 27 kg embodied CO2-eq per kg ICT product. Although not discussed in this study, the emissions due to operational use are appreciable, depending on the source fuel for electrical generation.

3.5.3 Model 3: Furniture systems

The furniture systems in CIRS are manufactured and supplied by Haworth. The corporation is committed to using LCA as part of their Design for the Environment (DfE) strategies. The furniture systems, which include integrated office systems of walled office area, cabinets, tables, and chairs, are designed to be adaptable. Each element was modeled in-house by Haworth individually, with the seating systems following the BIFMA Seating Product Category Rule: UNCPC 3811. The models include impacts of the manufacturing operations and transportation impacts to the Haworth assembly plant in Michigan and to the end customers. Haworth supplied the results of their studies, not the actual models themselves.

The impact assessment method for all Haworth models is TRACI 2.1 V1.00/US-Canadian 2008. Additional steps are taken for the seating systems. To conform with BIFMA Seating PCR UNCPC 3811, transportation data was collected utilizing methodology from the USEPA Waste Reduction Model (WARM) and the U.S. Department of Transportation's Research and Innovative Technology Administration (RITA) website's 'TranStats'; and city-specific electricity data was modeled using the USEPA eGRID. Transportation distances are specified in the Haworth models, but these details, along with other key aspects of the Haworth supply chain, are not discussed in this dissertation, to respect Haworth intellectual property.

3.6 Data quality

The data quality is reported in Table 3.2 and is reported qualitatively by the authors, with the aim of locating model weakness. Quality is reported using a simplified 'pedigree' matrix as required by LCA standards (Junnila & Horvath 2003; Weidema & Wesnæs 1996). Overall, the greatest area of concern is the Athena EIE database, which is problematic in terms of lack of transparency for LCI details. Nonetheless, data age is known and a considerable volume of data has been updated in the past 10 years (ATHENA 2012).

Table 3.2 Pedigree matrix for data quality.

Data	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technical correlation
ICT Data	Verified data based partly on assumptions, with some non-verified data based on measurements	Representative data from a sufficient sample of ICT devices, some assumptions and expert judgment	Less than 3 years of difference across source data studies	Some EU ecoInvent imported data from areas with similar production conditions	Very rapidly changing technosphere. Data obsolescence rapid.
Structural Data	Verified data based on proprietary databases. Review internal to Athena.	Representative data based on a sufficient number of measured buildings.	Less than 5 years of difference between individual studies. Some EIE data over 10 years old	Average data across continental scale. Transportation distances based on Vancouver location	Slow change in techosphere. Production and transportation systems slowly evolve
Furniture Systems Data	Verified data based on measured but proprietary data	Representative data from an adequate number of sample points	All data under 10 years.	Data from area with similar production conditions	Moderate changes in technsphere. Systems under study well understood.

3.7 Life-cycle impact assessment method

Environmental impacts are derived from the *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts* (TRACI) categories. However, TRACI versions used in the study are not fully consistent. TRACI 2.1 is used for the ICT model and furniture systems, whereas TRACI 2.0 is used for the structural systems (see Table 3.3). Unfortunately, this means that directly comparing model outputs for most categories is avoided except for GWP, which is consistently calculated with IPCC 2007 GWP100 impact characterization method between V2.0 and V2.1 methodologies (Goedkoop et al. 2008). Note that the IPCC have recently revised the GWP calculation with increases for the climate forcing effects of methane. This is an important consideration for comparing these results against future studies (IPCC 2013).

For building systems and ICT, selected impacts are shown from the main categories: primary energy use (kWh eq), global warming potential (kg CO2 eq), acidification potential (moles H+ eq), eutrophication potential (kg N eq), ozone depletion potential (kg CFC-11 eq), smog potential (kg NOx eq), and human health (HH) respiratory effects potential (kg PM2.5 eq). Impact analysis is based on ISO 14044 (ISO 2006a) and ISO 14040 (ISO 2006b) guidelines.

Table 3.3 LCIA data methods for each LCA model with respect to building type.

	Structural	**ICT**	**Furniture systems**
CIRS	Athena EIE V4.0, TRACI 2.0	ecoInvent 2.0 TRACI V2.1	ecoInvent 2.0 TRACI V2.1
AERL	Athena EIE V4.0, TRACI 2.0	ecoInvent, 2.0 TRACI V2.1	N/A
UBC	Athena EIE V4.0, TRACI 2.0	N/A	N/A

3.7.1 Functional unit

A functional unit is defined as a quantified performance of a product system for use as a reference point. Within the context of ISO 21931-1, functional equivalence for buildings is based on similarity of building type, occupancy patterns and design life. The functional unit is herein defined as ‘a whole building constructed to function as a combined classroom and office, with occupancy expected for academic use.’ The functional physical units are defined as *impact/m^2/yr*, annualized over 50 years. The normalization is respect to unit floor area so that data can be compared to the UBC-Database averages. Challenges in defining the functional unit include the sharply differing churn rates of each technology. Figure 3.1 shows the relative lifespans of components used in the model (Teehan & Storey 2012), (CMHC 2000), (Bowick 2013). Note that the large spread in service life for structural elements is due to the broad spectrum of building components e.g. rapid replacement of surface finishings versus long-lived concrete foundations. In terms of setting a time interval for the integrated model, a 50-year cut-off is obviously arbitrary, but is set at a long-enough time scale to capture at least one, or ideally several, iterations of each component within the integrated model.

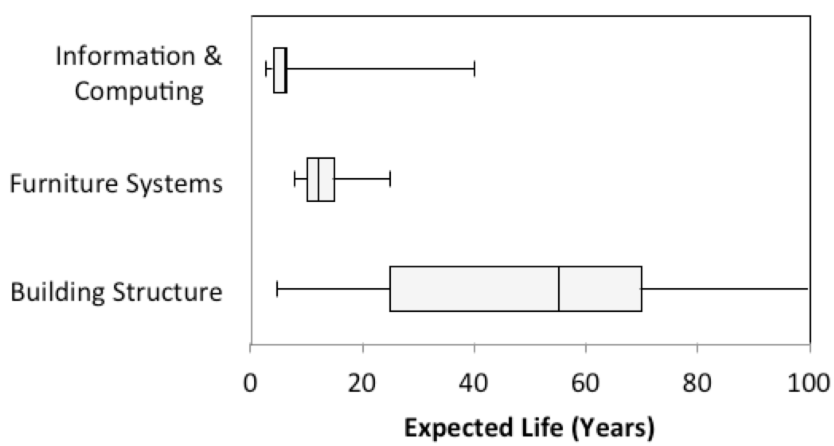

Figure 3.1 Life spans of components (quartile distributions).
The upper extremity observable in the IT dataset is due to the Cat5 internet cabling which is expected to last 40 years.

An additional issue is the high levels of uncertainty with regards to the evolution of ICT over time. Any extrapolations beyond 5-10 years are likely to be uncertain, and any projection between 10-50 years likely to be *highly* uncertain. There are several technological long-term trends already observable, including de-materialization (Wernick et al. 1996; van den Bergh & Janssen 2004) and increasing energy and carbon efficiency of the supply chain (DOE 2012) which are expected to lower long-term future impact for ICT services.

In contrast, many building structural technologies are comparatively stable and slow to evolve with only incremental change to the production of materials, such as concrete or glass. In terms of durability, furniture system life spans are situated between ICT and structure, with lifecycles between 3-20 years. However, a change in tenant or building use can potentially end service life early. In the context of University buildings, service life is expected to be long, whereas with commercial retail premises service life is often curtailed by changing tenants, aesthetical obsolescence or resale. The impacts of churn rates are explored in the analysis and are a defining feature of this study

3.8 Results and discussion

The first three sections of the results discuss initial embodied impacts (no recurring impacts). These one-off initial impacts are relevant for analyzing the environmental outcomes of construction decisions made at the beginning of the design cycle. This includes a detailed analysis of the material choices for CIRS' structure (wood versus concrete).

The fourth and final section of the results discusses recurring impact. These cyclical impacts are relevant for analyzing the outcomes of future purchase decisions during building operation, particularly during tenant change-over when many interior changes occur.

3.8.1 Model 1: Initial embodied impacts for building structure.

The structural comparison results are shown in Figure 3.2, in which selected TRACI impacts categories are shown with respect to construction and manufacturing related impacts. All data is normalized and compared to the UBC-LCA data-base average and shown for AERL (LEED Gold) versus CIRS (regenerative).

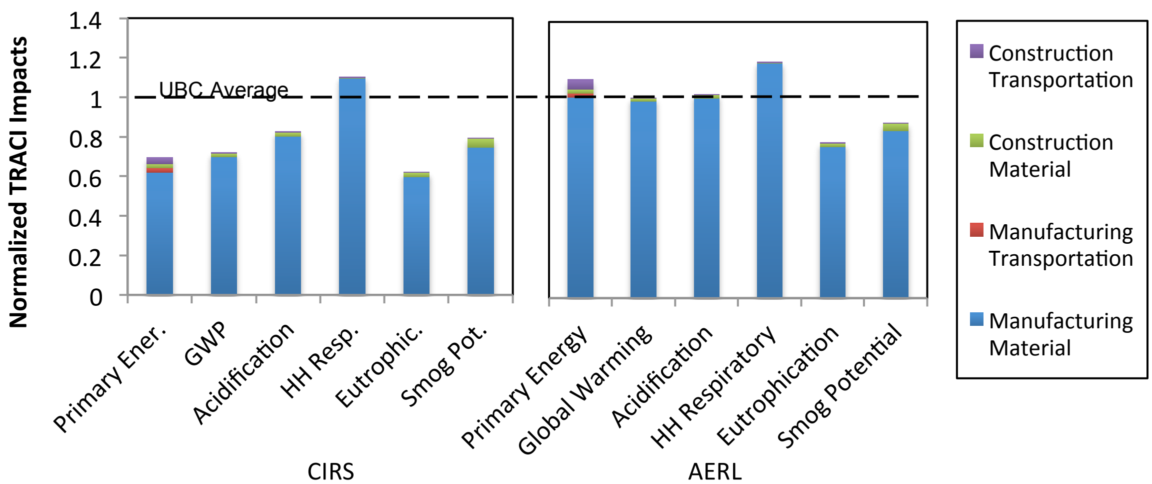

Figure 3.2 LCIA impacts for LEED Gold base-case versus CIRS.
The impacts shown are for TRACI LCIA categories and normalized to the UBC average for office/classroom buildings.

Overall, the CIRS design shows environmental improvements for many TRACI categories. In contrast, the results show AERL is slightly less impacting than the UBC average for eutrophication and smog potential. Other impacts are close to the UBC average, slight deviations from the average should be treated with caution, because of uncertainty throughout the models. CIRS shows reductions for six of the seven metrics by a large margin of 20-40%. Human health (HH) respiratory impacts are higher for both models, which is potentially significant. Unfortunately the Athena tool does not easily enable an exploration of direct impact of specific materials. Further work is required to identify which materials are causing the higher HH respiratory impacts.

Almost all impacts occur in the manufacturing phase, with only a small percentage being attributable to either transportation from fabrication to site or on-site construction activities. This finding is in agreement with (Junnila 2009; Verbeeck & Hens 2010) and others. CIRS favoured the use of local materials to reduce environmental impact, as is mandated by the Living Building Challenge, a certification process followed by CIRS during design and construction. However, the results show that only a small proportion of impacts are associated with transportation, which suggests that rewarding localization for environmental reasons is overemphasized. Transportation impacts are strongly correlated to transportation mode, rather than simple metrics of distance (Horvath 2006). Greater environmental benefits could be gained by rewarding efficiency at the extraction phase and later at the manufacturing phase.

3.8.1.1 Strategies for reducing embodied GWP

Concrete is documented as being highly energy intensive during production (ATHENA 2005; Ochsendorf et al. 2011). This motivates a careful examination of its use throughout the models. The results for the case-study buildings, shown in Figure 3.3, indicate that concrete dominates the mass of both base cases and the UBC average. Overall, CIRS is 46% lower in concrete use than the UBC benchmark, which is attributable to the displacement of concrete with structural wood components. Concrete by mass ratio with respect to the sum of all other materials is 6:1 for the UBC average and 3:1 for CIRS. With respect to wood only, the mass ratio of concrete to wood is 170:1 for the UBC average and 8:1 for CIRS. Volumetrically, the relative densities of wood to concrete mean that wood products occupy a more significant physical footprint. The volume ratio of concrete to wood for CIRS is 1.4:1. Furthermore, concrete is largely confined to the basement area, office bar supports and floors, which leads to an emphasis of wood throughout CIRS occupied areas. In terms of impact reduction for GWP, the model results, as shown Figure 3.3, indicate that the main driver of impact is the use of concrete. The two case-study buildings approach impact reduction by two methods; CIRS uses wood to 'offset' CO2eq and both buildings use fly ash to replace cement.

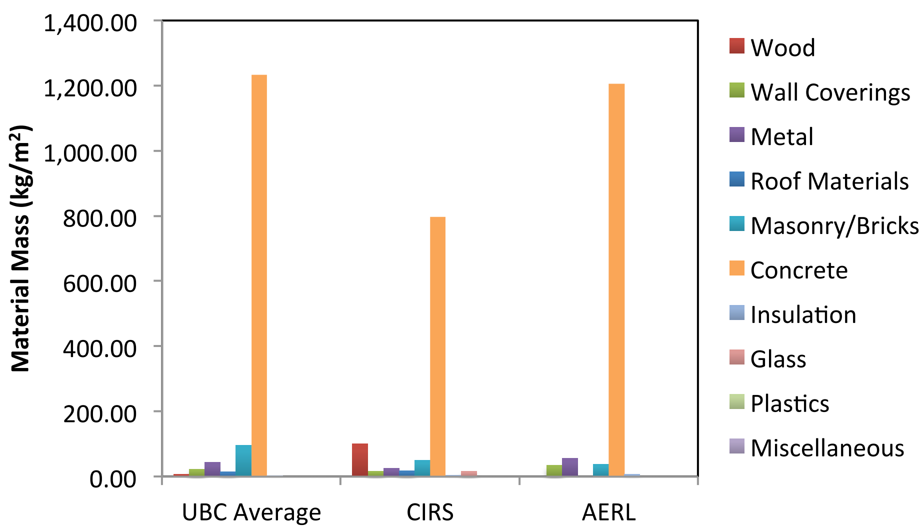

Figure 3.3 Mass of building materials, normalized by area.

With advanced wood technologies enabling the construction of taller than four-storey buildings, the use of structural wood for carbon storage has become a viable solution.

However, the calculation method for crediting wood for sequestration is contested and the fundamental methodology has yet to be agreed. The inclusion of various supply-chain impacts, including land-use change in harvest cycles, wastage and secondary-product generation and end-of-life custody, causes large model-based uncertainties for embodied impacts (Werner & Richter 2007; Gustavsson & Sathre 2006; Ng et al. 2013; Fernandez 2008; Masanet & Stadel 2013; Salazar & Meil 2009). Whole-life LCA, including operational energy, is even more problematic. Poorly defined system boundaries mean that study results appear in contradiction. For example, Upton et al. (2008) report that houses with wood-based wall systems require 15–16% less total energy than alternate construction materials (Upton et al. 2008). On the other hand, Nässén et al. (2012) report that concrete frames cause about the same emissions as a wood frame in a system where carbon capture and storage are not used for wood incineration in the demolition phase (Nässén et al. 2012). Ochsendorf et al. (2011) found that concrete buildings have similar emissions over 60 years as compared to steel and wood alternatives. However, their model assumes that concrete buildings have superior insulation properties over the base-case buildings (Ochsendorf et al. 2011). Overall, the model results can vary according to how modellers treat system boundaries; arbitrarily omitting, or including, key aspects of the building's systems can change the model's output and interpretation. A full critique of the methodological challenges is beyond the scope of this analysis. For illustrative purposes, a sensitivity analysis is shown in Table 3.4 using two different allowances for CO2eq 'storage', a lower conservative approach based on carbon storage within the building footprint and an upper value that includes benefits on the wood supply chain. A figure of 0.76 t.COeq/m^3 is a conservative lower value based on the actual carbon locked in the structural wood. The upper value of 1.6 t.CO2eq/m^3 is obtained from studies by Forest Product Innovations (FPI), which includes the wood supply chain processes including subsidiary secondary use of wood use in the forest production phase (Sathre & O'Connor 2010). The results show that 64% carbon reductions are achieved using the lower value, and 135% for the higher FPI value (>100% means the structure is carbon positive).

The second approach to impact reduction is the use of fly-ash displacement in concrete. Both case-study buildings use fly ash throughout the structures, with proportions dependent on the strength requirements of each structural member. The reduction potential for the extensive use of fly ash in CIRS' concrete systems is 6-9%. The actual values attained by CIRS and AERL are 8 and 11%, attributable to a variety of levels, 35% flash ash for walls, 25% for floors, and a combination of 25% and 35% fly ash for the foundations. In general, CIRS used slightly higher proportions of fly ash in structural concrete but with AERL having over 400kg/m^2 more concrete than CIRS, the overall benefit is higher for AERL.

Table 3.4 Carbon reduction strategies for CIRS and AERL.
Values greater than >100% indicate a carbon 'positive' value (more CO2eq stored than emitted in construction process).

Carbon Reduction Strategy	CIRS	AERL
Reduction for CO2 storage credit for wood (0.76t.CO2eq)	64%	0.03%
Reduction CO2 storage credit for wood (1.6t.CO2eq)	135%	0.07%
Reduction for 25% fly ash	6%	8%
Reduction for 35% fly ash	9%	11%

The two strategies have benefits for reductions, although the fly-ash reductions are limited. The use of structural wood enables deeper reductions, but the permanence of storage gained by using structural wood is highly dependent on the end-of-life custody for wood re-use. Wood products must be re-used at end-of-life for the building to ensure that CO2eq storage is persistent. With CIRS using design-for-deconstruction practices, there is a reasonably good chance that the bolted wood beams can be reused, which would preserve the storage past building end-of-life.

Although both strategies, the use of fly ash and wood, were employed in CIRS to obtain carbon 'positive' status, a late addition to the building design increased the CO2eq burden. An extensive concrete basement was a requirement for CIRS to replace pre-existing campus storage that had to be demolished to make room for the new building. Of the total concrete in each respective building, 72% of concrete systems are below grade in CIRS, compared to only 30% below grade for AERL. This increased the GWP for CIRS basement to 134 kg.CO2eq/m^2, compared to 85 kg.CO2eq/m^2 for the AERL basement.

3.8.2 Model 2: ICT initial embodied impacts

ICT systems in the case-study buildings are modeled using data from (Teehan & Storey 2012), which analyses a portfolio of components based on an estimated number of devices installed in both case-study buildings. The occupancy of the buildings is comparable, with a similar number of occupants and academic usage patterns. A distinct feature of the ICT mix for CIRS is a building-wide use of thin-clients, which reduces material impacts and operational maintenance cost. AERL differs in that it relies on a mix of laptops and PC towers. However, both buildings have a similar number of peripheral devices such as LCD monitors, keyboards, and wireless access points. Figure 3.4 shows the relationship of the number of devices to their initial installation impacts (fit-out mix in first year of building operation). Both buildings have a large number of low-impact peripherals. In contrast, LCD monitors have a disproportionate initial, or 'cradle', impact. The GWP impact of CIRS is 76% of AERL. The difference between the two systems is moderated by the large number of LCD monitors which is identical in both buildings. In other words the large aggregated impacts of LCD monitors dilutes the benefit of the thin clients.

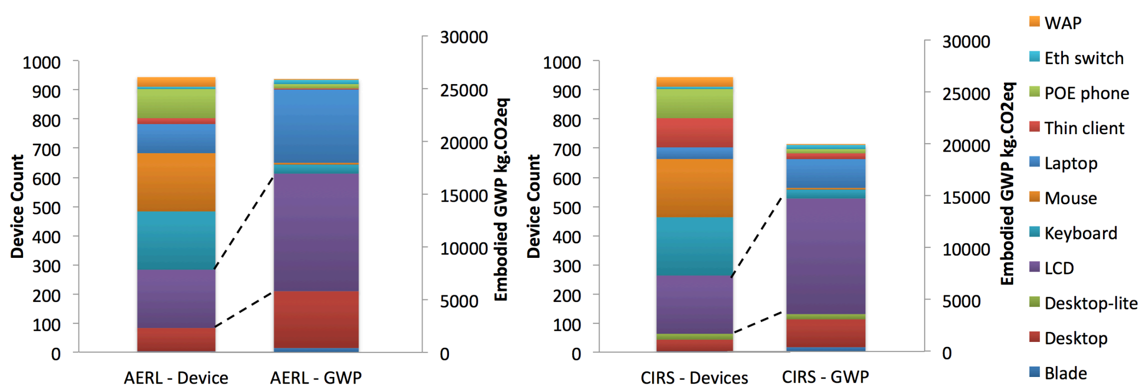

Figure 3.4 Number of devices and initial GWP embodied t=0 impacts for AERL and CIRS. The disproportionately large impact of LCD monitors is highlighted with the expansion fan between the device and GWP stacked bar charts.

The initial installation impacts are shown in Figure 3.5 for TRACI metrics normalized to the model average (no UBC campus average is available). Two main findings can be observed; firstly, that most impact categories scale closely to one another. This means that, at least for initial embodied impacts, examining any particular impact factor category such as GWP is a fair approximation for the magnitude of other category impacts. The second finding is that, from an embodied point of view, CIRS' performance is slightly better than AERL's, mainly because the thin-client approach reduces the overall material requirement at office desks at the small cost of extra servers for computational processing. The thin-client based IT mix initially saves 31kg.CO2eq embodied impacts per user. This is lower than the 80kg.CO2eq reported by (Maga et al. 2013) for the material and extraction phases; likely the differences are due to different data sources in that study.

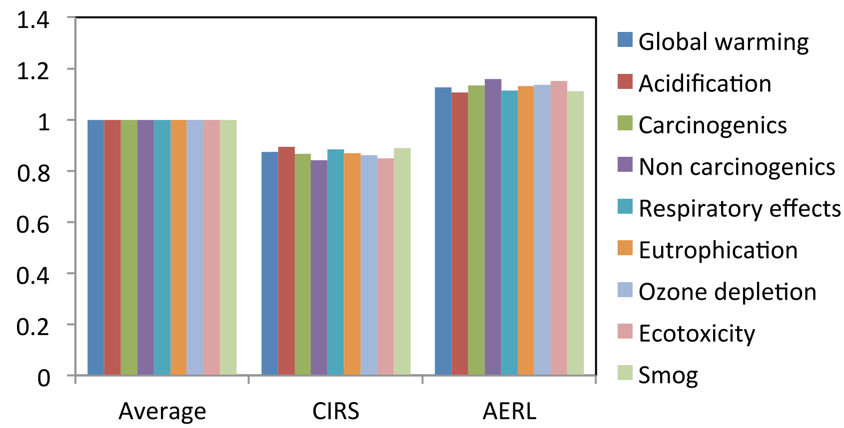

Figure 3.5 TRACI LCIA initial t= 0 results for CIRS versus AERL.
The data is normalized to impact average. Note that there is no UBC-wide average value due to data limitations regarding the campus IT mix.

3.8.3 Model 3: Initial embodied GWP impacts for furniture systems

The furniture systems include all moveable systems that include office furniture along with storage and meeting room furniture. The fixed seating system for the auditorium, along with carpeting, is not included. The number and types of devices in CIRS, along with associated GWP impacts, are shown in Figure 3.6. The bulk of the impacts are found in the workstation equipment, which includes low walls with considerable metal support structures. The seating, though numerous, does not incur large impacts. Again, there is considerable uncertainty with respect to product life span, which is highly dependent on tenant care, use and changes in aesthetic preferences.

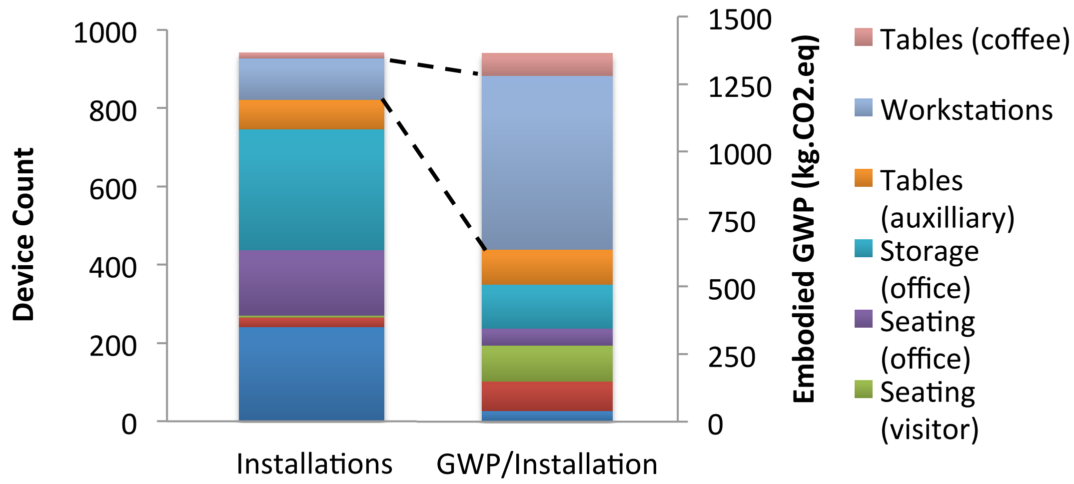

Figure 3.6 GWP LCIA initial t=0 impacts for CIRS furniture systems.

Only GWP impacts have been obtained from Haworth, so the results are more limited in scope than for structural and ICT systems. Additionally, there is no benchmark data for AERL, although these impacts are expected to be similar, due to the open-office outlay.

3.9 Recurring Impacts: Integrated ICT, furniture and structural LCIA

The combined impacts of the three models in Figure 3.7 shows the long-term increases in embodied energy. The figure shows the aggregated impact, with each successive year adding to the impacts to the previous year's accumulated total. The building structure recurring impacts are annualized, and hence artificially smooth in the figure. This is due to Athena EIE not explicitly revealing the timing of each renewal, and instead producing a total recurring impact. The ICT results are a sharp contrast to the building structure impacts. ICT have a very rapid churn rate, with life spans of 3-6 years (as shown in Figure 3.1). The ICT trends are highly uncertain beyond all but the shortest time intervals and are displayed for illustrative purposes only. With this caveat in mind, the figure shows that, after 50 years of service life, the GWP impacts of ICT and furniture systems are of the same order of magnitude as the building structure.

The ratio of initial to embodied impacts differs sharply between components. Over 50 years, for structural systems, total recurring GWP impacts are 12% of initial impacts. For furniture and ICT, high churn rates cause elevated recurring impact ratios of 460% and 1000% respectively. These relative ratios are not static and will change as technology evolves; for example, if computer hardware technology dematerializes (requires less physical hardware) over time, then the ICT ratio will become progressively smaller. Technological change, and the timing of impacts, for each system have very different implications for planners. Structural technologies evolve slowly, and recurring impacts are unlikely to change significantly over time. From a planning point of view, strategies that reduce impacts at the point of construction are more accessible than reductions later in building life. In contrast, for furniture systems, the upfront impacts are small, but the repeating churn-based operational impacts are high. From a planning point of view, the question of durability and adaptability is a driving factor for impact reduction. Considerable gains can be found during service life-cycle by careful decision-making at each churn point. Much less can be said about ICT systems, because both the mode of information service delivery and the technology are evolving. Decision-making is much more challenging in this context. On one hand, rapid dematerialization of ICT reduces material throughput during manufacturing, but conversely, there is a proliferation in the number and variety of devices. Additionally, there is a trend towards cloud-based information delivery, which is pushing impacts outside of the building envelope towards centralized server systems. Building managers need to consider ICTs with a different decision lens than furniture and structural systems. A further complication is that durability for ICT products is not always a useful goal, because obsolescence often precedes the device service life. Purchase decisions will need continuous optimization and analysis to quantify both the effects of globalized service delivery and shifting supply chains.

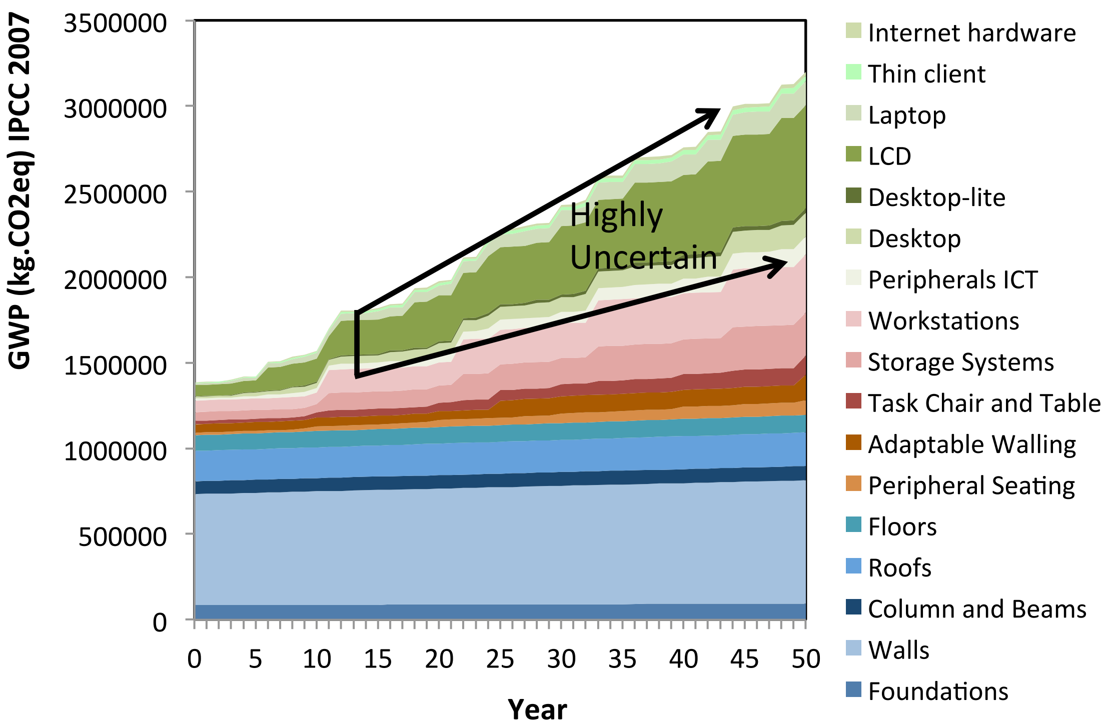

Figure 3.7 Embodied GWP results for CIRS for 50 years of use.
ICT impacts are highly uncertain beyond +10 years of technological evolution. Initial embodied impacts for the three models are visible at t=0.

A correlation of GWP and product mass can be found by examining the GWP impact per device mass, as suggested by Teehan et al. (Teehan & Storey et al. 2011). The mass-GWP impact relationship, shown in Figure 3.8(a), reveals linear trends for other building systems. Teehan et al. finds a linear coefficient of 27 kg CO2-eq per kg for annualized ICT impacts (which is identical to the data used in this study). This rises to 31.4 CO2-eq per kg for non-annualized embodied impacts. The coefficient for furniture systems is calculated at 1.3 kg CO2-eq per kg. This compares closely to (Dietz 2005) who have slightly higher impact ratios of 2.1 to 7.4 CO2-eq per kg; for similar desk and chair products. The furniture systems have less impact per unit mass than ICT, because the latter is more resource intensive in the extraction and manufacturing processes. ICT subcomponents such as PCB, displays and batteries have particularly high impact. For structural systems, the coefficient is ~0.2 kg CO2-eq per kg however, the correlation is low, indicating considerable uncertainty. When recurring impacts are considered, the relative impacts change considerably. Figure 3.8(b) shows cumulative impacts after 50 years of iterating churn changes. The ICT and furniture approach the same level of GWP impact as the structural systems, but their total 50 year mass is still much less than the structural systems.

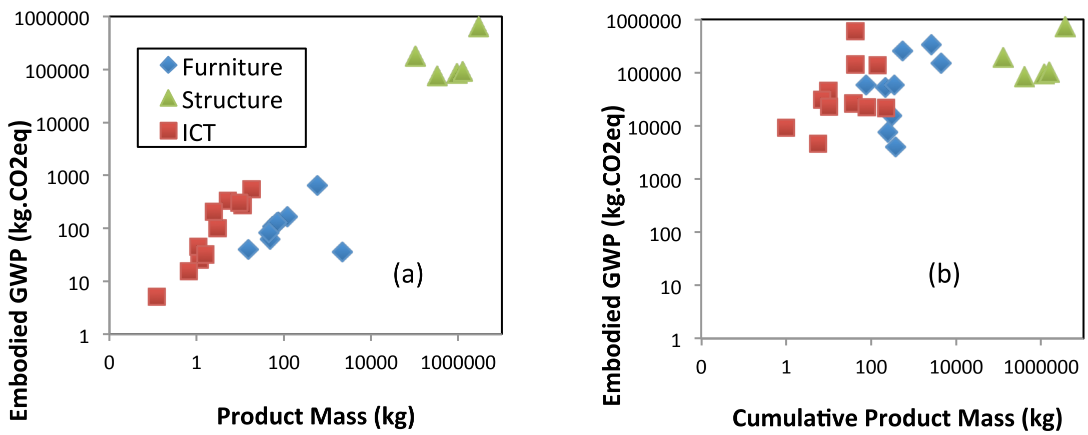

Figure 3.8 Embodied GWP with respect to product mass.
Note that a log-log scale is required to scale for the numerically large construction mass and impacts. (a) shows the embodied impacts at t=0 and (b) shows the aggregated impacts at t=50. Uncertainty is high for ICT systems.

The mass-impact approach, though simplistic, indicates there are possibilities for rapid estimation of environmental performance by assessing the aggregated masses of products. Overall, the order of magnitude difference observable between each of the three component groupings indicates a possible new approach to conceptualizing impact. Very approximately, ICTs have 10 times the impact per unit mass of furniture systems and 100 times the impact of structural systems. This relationship is a multiplicative product of the relative product lifespans (ICT being relatively short) and the with impact intensity per kg (ICT being relatively high). Further work is required to see if this approach can inform a rapid assessment prototyping method for building designers and managers. If prospective interior systems can be estimated by weight, the linear mass-impact relationships enable an order of magnitude estimate of the potential environmental impact. Fast estimations can be conducted as a screening analysis to identify hotspots which could be followed by more a detailed analysis to drill down on more specific design options.

Overall the comparison between impacts can be seen in Figure 3.9(a) and (b), which shows how the relative impacts compare after 0 and 50 years of use, respectively. The structure remains the largest contributor, with furniture and ICT becoming significant over the long term. The stored CO2eq in the wood structure is not enough to approximately offset the ICT impacts or furniture impacts, but is enough to significantly reduce the overall combined impacts.

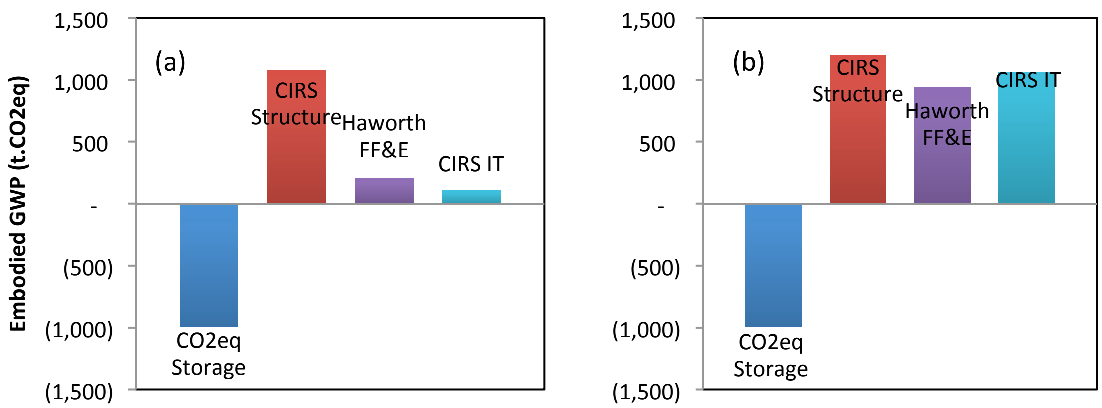

Figure 3.9 Embodied GWP for CIRS with respect to (a) 0 years of use and (b) 50 years of recurring impacts.

3.10 Sensitivity analysis

Of the three models, the ICT and furniture systems are most susceptible to recurring impacts. With product life span being the key determinant of long-term impact recurring impacts, a sensitivity analysis is conducted for the CIRS systems by analyzing feasible changes to service life on these high churn rate models. Figure 3.10 shows a select number of numerical experiments on the model for 30% changes to the durability constants for the ICT and furniture systems. A shortened life span in (a) has a large effect and causes recurring impacts to increase rapidly compared to the base-case and exceed the structural systems in years 37 and 48 (ICT and furniture, respectively). A longer lifespan, as shown in (b), ensures structural impacts are not exceeded. However, as mentioned, the long-term trend for ICT is unknown, so the results should be treated as illustrative only.

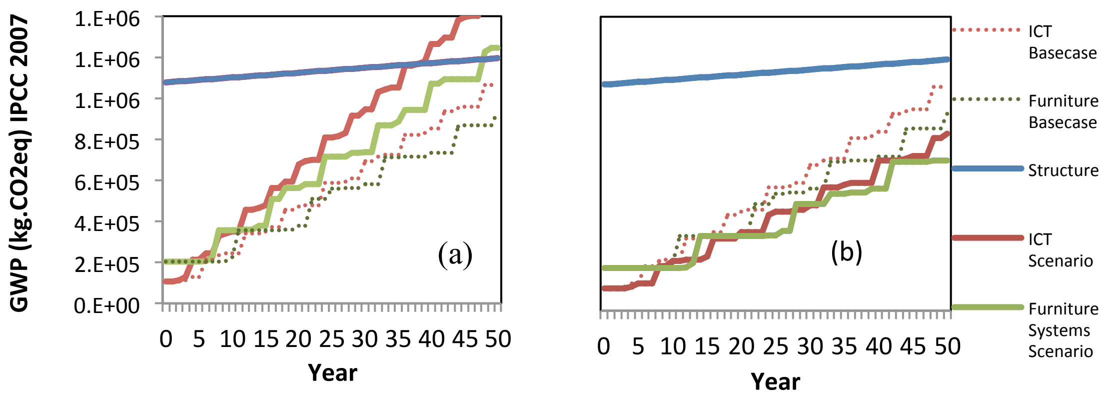

Figure 3.10 Sensitivity experiments examining recurring embodied impacts. Structural impacts are held steady while (a) shows the effects for an extended life of 30% on ICT and furniture systems, (b) shows effects of a reduction of 30% in life span. Uncertainty is very high for ICT.

The sensitivity analysis in Figure 3.11 shows the effect of improvements in carbon intensity of economic output for the OECD, which is anticipated to become approximately 10% more carbon efficient by 2040 by the Energy Information Administration (EIA) Carbon intensity of economic output is a measure of carbon dioxide emissions per dollar of GDP (CO_2/GDP) (EIA 2013). EIA data is used in the sensitivity experiment until 2040, which is the last year of their prediction. The remaining data required for the model (2040 to 2063) is assumed by linear extrapolation of the overall EIA trend. Further assumptions are that carbon efficiency gains in the economy are reflected in the overall life-cycle impacts of the products and that most products are manufactured in North America. Both assumptions are feasible, although supply chains may continue to globalize over time and products are sourced from overseas. This is not necessarily a problem if, as expected, the carbon efficiency of economies converges between global production regions.

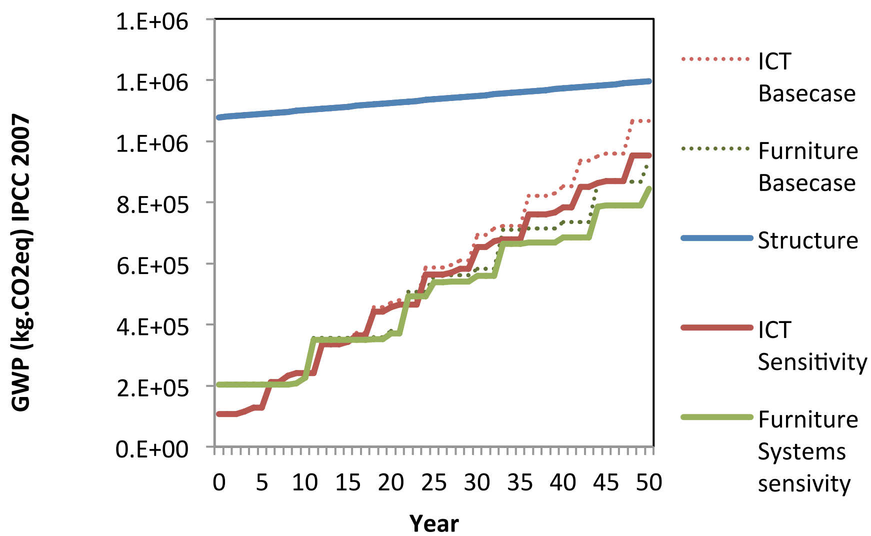

Figure 3.11 Shows the impact reductions attributable to possible IEA predicted carbon efficiency gains in the production economy.

The results show overall reductions in impacts but are not as significant as the other sensitivity results in (a) and (b). Carbon efficiency gains cannot be relied upon to significantly 'bend down' the curve. Further analysis could be conducted on estimates on long-term mass dematerialization of ICT, which is qualitatively viewed as a feasible future. However, no data is currently available for evaluation, which means a sensitivity analysis is not conducted.

Caution should be applied with respect to the policy implications of this study. The operational impacts of building systems are not analysed in the study. Operational impacts, of course, vary according to the consumption of the ICT devices and this will increase their overall impact relative to passive devices such as FF&E and structural systems. A detailed study of operational impacts is discussed in Teehan et al. (2012). However, the intent of the study is not to point out the relative operational versus embodied impacts (this is discussed in detail in Chapter 4 at the building scale), but rather to point out that, from a policy point of view, a reduction in recurring embodied impacts can potentially be attained by identifying specific points of intervention. The intervention timing is frequent in the shorter-lived systems, such as ICTs. This is contrast to the long-term embodied impacts of building structure, which is essentially fixed at construction. Recurring impacts due to construction upgrades and maintenance ads only 12% to the overall GWP impact load over 50 year time-span.

For embodied impacts, the relevant points of intervention in the three systems correspond to their turn-over rates. The turn over rates (with respect to the upper and lower quartiles) are — ICT 2-8 years, FF&E 23-70 years and for construction components 5-70 years (or end of life). Similarly, operational impacts are relatively fixed for construction systems (upgrading an envelope is expensive and invasive) but efficiency improvements for ICTs are much more frequent, leading to potential operational gains at the point of renewal. From a decision-makers of view, it easier to reduce embodied impacts by understanding the points of intervention in terms of timing and leverage. This motivates four main strategies:

:

1. Reduce construction impacts at the outset of design because lock-in will last for decades, or possibly the entire life of the building
2. Identify the timing of replacements relative to their churn rates so that interventions can be planned in advance
3. Continuously optimize and update LCA models so that any technological changes, or alternations to life span, can keep the model up to date.
4. Plan for disposal and recycling. Understanding when devices are approaching end-of-life can enable pro-active waste management strategies

3.11 Conclusions

Three building-related systems are modeled for a 50-year period and analyzed in terms of a select group of TRACI impacts. These include structural systems, ICT fit-out and furniture systems. Two levels of building performance, LEED Gold and a regenerative standard, are compared for ICT and structural systems.:

- When compared against the UBC average impacts for offices, the structural impacts show an overall improvement for CIRS (regenerative) in terms of reductions across six of the seven TRACI metrics by a margin of 20-40%. No consistent improvements are found for AERL (LEED Gold).
- The use of wood and fly ash are investigated in terms of effectiveness in reducing GWP impacts. The use of structural wood decreases the potential impact of CIRS by 64% or 134% (depending on the coefficients used) and the use of flyash decreases impact by 8%. Storage of CO2eq by wood is highly dependent on the

end-of-life fate of the structural systems. Failure to re-use timbers may mean CO2eq could return to the atmosphere.

- The transportation impacts are found to be small, which brings into question the effectiveness of the localization policy encouraged by LEED and the Living Building Challenge. This finding matches previous studies that show that, for freight shipping, transportation *mode* is more important than *miles travelled*.
- While none of the TRACI impacts of CIRS are visible as being regenerative (this would be observable as negative impact — i.e. values below the x-axis), the focus on reducing GWP has closed the gap towards attaining net zero for carbon storage.
- Caution must be taken with regards to use of LCA to answer many questions anchored in regenerative thinking. LCA is relatively narrow in scope and other attributes of operation, such as regenerative gains in human comfort and health, need further analysis using other assessment approaches.
- The combined LCIA results show that, particularly over the long term, systems with high churn rates aggregate significant impacts over decadal periods of time, though there is very great uncertainty about the specific magnitudes. The building structure incurs a single large embodied impact at construction and then slowly accrues recurring impacts to a total of 12% over 50 years. In contrast, assuming that impacts per unit of equipment remain constant over time, the total recurring impact of ICT and furniture exceed their initial impacts by 460% and 1000%, respectively.

- Sensitivity analysis shows that total aggregated impacts are highly sensitive to the life spans of each device, particularly devices such as LCD monitors that dominate the overall impact burden. With IT have very short innovation cycles, aggregating impacts over the long term generates high level of uncertainty and results should be interpreted cautiously. Achieving small predicted increases in macro-economic carbon efficiency gains over the long term is found to produce only small impact improvements.
- The embodied impacts of devices are found to scale linearly with their mass. This trend opens possibilities for simple benchmarking and an informative heuristic at the design stage for new buildings. The ICT coefficient is 31 kg CO2-eq per kg, the furniture systems is 1.3 kg CO2-eq per kg and the structural system coefficient is, approximately, ~0.2 kg CO2-eq per kg.
- The UBC-LCA database offers a preliminary dataset for local benchmarking and is useful for designers who would like to track progress towards design targets. Similar regional efforts are recommended for other institutions or community scale efforts.

Overall, light but fast-moving high-impact products such as ICT and furniture can only be compared against heavier and slower moving moderate impact products such as structural systems by examining relative time scales carefully. Conceptualizing potential environmental impacts is better informed by considering a temporal context to replacement decisions. The results show that it is possible to reduce initial impacts by careful material consideration before construction, but the initial gains can easily be lost by not properly evaluating operational recurring impacts. The results also give insight into the best life-cycle intervention strategies to gain impact reductions. A good leverage point for reducing the impact of structural technologies is at the construction phase, because solutions later in building life are harder to find. Conversely, rapid metabolic systems such as ICT and furniture require continuous evaluation during building life. The leverage points for fast-churn systems consist of numerous, but smaller, opportunities at every purchase point during building life.

Chapter 4: Comparing LEED and Conventional Buildings: the Life-cycle Environmental Impacts of 80 University Academic Buildings over a 90-year Construction History

4.1 Summary

Process life-cycle analysis is used to compare life-cycle impacts of 10 LEED buildings against 70 conventional buildings at the University of British Columbia Vancouver campus (UBC-V) built over a 90-year construction history.

Firstly, for construction phase impacts, the embodied energy and global warming potential (GWP) of UBC-V buildings is coupled to construction year. Embodied impacts have risen steadily due to the increasing use of structural concrete.

Secondly, the operational performance of UBC-V buildings is highly variable. The strongest determining factor for performance was building type, with laboratories using 90% more than the UBC-V stock average. In contrast to the embodied trend, building age was found to have very little influence on energy consumption. There is no significant trend in energy performance improvement for buildings constructed from 1920 - 2010. LEED-building performance is similarly highly variable. Overall, UBC LEED buildings, as constructed from 2000 – 2011, afford no guarantee of improvement over conventional buildings.

Thirdly, understanding community scale changes in terms of population intensity is important for contextualizing the building scale dynamics. While metrics such as EUI are useful for tracking performance by area, they do not reflect use by the community at

large. Increases in population density reveal that performance has improved for impacts per person.

Finally, combining embodied and operational impacts of buildings reveals complicated relationships between different environmental indicators. For GWP and primary energy, the impacts are over 90% attributable to operation, which is in agreement with the literature. However, compared to operation, the construction phase (including manufacture) greatly increases other indicators such as eutrophication and acidification potential. Institutional stakeholders are most interested in GWP and energy, since these incur budgetary costs. However, if they are interested in going beyond best-practices, they will need to examine and understand a more comprehensive set of environment impacts and look beyond GWP.

4.2 Supporting participation and acknowledgment statement

Data and modelling contributions: Lillian Zaremba, Climate and Energy Engineer (UBC University Sustainability Initiative), UBC Operations Technology, Rob Sianchuk (Instructor, UBC)

Decision stakeholders: UBC University Sustainability Initiative

Co-authors: Lillian Zaremba, Climate and Energy Engineer (UBC University Sustainability Initiative), Rob Sianchuk (Instructor, UBC)

Mentorship: UBC LCA Alliance

4.3 Introduction

Public institutions across North America are developing sustainability plans to improve their built environments. The ability of public institutions to navigate the difficult path to sustainability has been constrained by internal institutional barriers, budgetary limitations, and to a lesser extent, expertise silos (Richardson & Lynes 2007; Gudz 2004). For universities, the challenges are further magnified by the difficulty of reducing absolute consumption while expanding research, educational and residential services. This dual challenge – growing while reducing impacts – is being undertaken by the Vancouver campus of The University of British Columbia (UBC-V) by implementing a broad set of campus-wide goals and strategies. UBC-V has an integrated approach to reducing maintenance deferral debt by improving building performance and proliferating applied sustainability research beyond academic research and into campus operations. For example, the UBC-V campus has self-imposed stringent greenhouse gas reduction targets, currently the most ambitious of any public institution in Canada. Targets are 33% reduction by 2015, 67% by 2020 and 100% by 2050, compared to a 2007 baseline (C&CP 2012). One of UBC-V's goals is to reduce utility and carbon tax costs while simultaneously expanding infrastructure and the campus resident population. The Vancouver campus is rapidly increasing in density, with 191,700 m^2 of new academic research space scheduled to be added between 2010 and 2030 and further expansion of multi-use residential hubs (C&CP 2010a).

UBC-V has a strong record of demand-side management, as exemplified by the ECOTrek program completed in 2001-2008, which achieved approximately 24% reductions in energy intensity (UBC 2012). While many of the easier demand-side strategies have been attained, there remains a persistent gap between future energy requirements and UBC-V's long-term goal of being carbon neutral. UBC-V is seeking to close this gap through improved building performance and intends to expand green building practices (UBC 2008). A central component of UBC sustainable building practice is the use of the LEED green building rating system. However, concerns have been raised with respect to the highly variable performance of LEED certified buildings (Turner & Frankel 2008; Diamond et al. 2006; Newsham et al. 2009; Scofield 2009). On average, building to LEED standards results in some improvement over Commercial Buildings Energy Consumption Survey (CBECS), and other baselines, but overall performance is highly variable, with between 28-35% of certified buildings performing below code. This has prompted UBC-V to carefully examine the ability of LEED strategies to be effective at reducing, in absolute terms, energy and carbon impacts. This study is motivated by the need to understand the implications of the continuation and expansion of LEED practices across campus. UBC-V is keen to understand how their built environment is performing across an array of environmental indicators. This study evaluates how GWP and primary energy are changing over time, and also examines other life-cycle impacts as defined by the US Environmental Protection Agency's TRACI metrics. These include external environmental impacts such as eutrophication, acidification, human health and smog potential, all of which must be controlled to reduce the burden to the global environment. The analysis uses life-cycle analysis (LCA) to examine cradle-to-grave impacts, including operational impacts and construction impacts, hence capturing the broader sense of whole building impacts. Additionally, UBC-V is interested in benchmarking performance of the existing stock and tracking relative progress with new buildings. Whereas previous studies have focused on a snapshot of performance, by either calculating the embodied or operational performance of buildings for a current year, this study shows how buildings are performing relative to the year of construction. With the building stock spanning over nine decades of construction history, a novelty of this study is an examination of whether newer buildings are performing better than older buildings. The study also examines community scale data to provide context to the building scale. While the work is not a full analysis of community-building scale relationships, the campus-wide data shows distinct improvement over time for GWP when normalized to per-capita metrics. These trends are not observable when only unit area impacts are analyzed at the building scale.

4.3.1 Goal and scope

LEED building performance is examined with respect to a historical construction practices on campus. The study takes the 'long view' over time and compares new green construction against the performance of buildings constructed between 1925 and 2012. To understand the total environmental impact of ownership, ISO 14044 methods are used to calculate life-cycle impacts of buildings in the core UBC-V building stock.

1. Embodied impacts are used to reveal how the impacts of construction materials have evolved over decadal periods of time. Embodied impacts for LEED buildings are compared with older, 'conventional' buildings.

2. Operational performance impacts are analyzed for a broad survey of core campus buildings. LEED buildings are compared against functionally similar conventional buildings.

The study findings can be used to inform building policy at large public institutions such as UBC-V and to frame technical guidelines for construction standards. With a serviced area of over one million square meters, along with a campus population of over 44,600 students and 14,000 faculty and staff, UBC-V operates on the scale of a small city (C&CP 2010b). As such, the campus can be considered 'municipal scale' and results may be informative for city planning purposes.

4.3.2 UBC-V context for energy and buildings

With UBC-V annually spending $17M on energy bills and associated carbon tax, the imperative has been on maximizing efficiency to reduce energy bills (UBC 2012). The recent introduction of the provincial regulation mandating carbon neutrality for the public sector has triggered annual liabilities of mandatory carbon offsets for UBC-V (C&CP 2012). While currently not required to be offset, Scope 3 emissions are of institutional interest, and UBC-V is interested in finding methods to achieve carbon neutrality for new buildings. Scope 3 emissions include the 'embodied' carbon emissions of construction. The control of emissions has been facilitated by UBC-V's status as an owner-operator for all academic and administrative buildings. At the community scale, a conversion of the campus district heating system from steam distribution to a hot water loop will produce a 22% reduction by 2016. The Bioenergy Research and Demonstration Facility (BRDF) will produce a further 9% reduction (C&CP 2012). At the building scale, there are two main initiatives. Firstly, BC Hydro's Continuous Optimization Program is underway (BCH, 2012), aimed at retro-commissioning 72 existing buildings with an overall efficiency improvement of 10% energy reduction by 2016. The second building scale strategy is to construct all new buildings to LEED Gold standards. The overall intent of LEED is to incrementally reduce environmental harm and include a number of measures to improve energy performance, ensure high levels of indoor air quality and improve occupant comfort. The LEED standard was further enforced by a province-wide directive in 2007 that requires all new public buildings to be built to LEED Gold equivalent or better. Hence, compliance with the provincial policy coincides with UBC-V's intent to build to high standards. Going beyond the provincial LEED Gold requirement, UBC's LEED Implementation Guide stipulates that certain credits are mandatory for design teams implementing LEED projects at UBC, including mandatory energy performance requirements (UBC 2013b).

In total, UBC-V will have 256,000 m^2 of either fully certified, or at least registered, LEED buildings by 2015 (UBC 2013a). UBC-V is also pioneering a 'regenerative' building design approach based on 'positive' outcomes. Regenerative design challenges designers to create buildings and neighbourhoods that contribute to social and environmental benefits instead of taking LEED's 'less bad' approach. UBC-V opened its first regenerative building, the Centre for Interactive Research in Sustainability (CIRS), in September 2011.

For the purposes of this study, ‘green’ is considered synonymous with LEED ‘equivalency’. While UBC-V has engaged the LEED process earlier than other public institutions, not all new buildings at UBC-V entered the official LEED certification process. However, all buildings since 2000 are minimally constructed to an equivalent level of quality high enough to satisfy the LEED Gold Provincial directive. Therefore, this study combines LEED certified and LEED ‘equivalency’ and compares this combined ‘green’ group against the ‘conventional’ building stock. The year 2000 is not a perfect dividing line; UBC began to explore green building practices as early as 1997, with the construction of the Choi building. However, the historical data shows that it was only after 2000 that buildings were predominantly built following strategies typically associated with green building design.

For this study, we compare ‘conventional’ versus ‘green’ standards and, to a lesser extent, ‘regenerative’ performance:

- ‘Conventional’ — defined as buildings designed and constructed without environmental impacts and energy demand concerns being considered directly at the core of the design process (pre-2000).
- ‘Green’ — defined as buildings constructed with direct consideration of environmental impacts and energy consumption (post-2000).
- ‘Regenerative’ — defined as a design philosophy that promotes restorative strategies. Only one UBC-V building, CIRS, has thus far been constructed to a ‘regenerative’ standard.

Comparing building performance has many challenges. It is technically difficult to measure across different regions and institutions, because of a large number of conflating variables, including differences in data acquisition, variations in building use, non-homogeneous reporting, and fuel-mix variation (Wedding & Crawford-Brown 2007). This study is a good opportunity to eliminate at least some of the variables due to standardized energy consumption reporting, identical climate zone and comparable levels of maintenance and upkeep. Campus occupancy variation at the community scale is well known. Classroom spaces are low occupancy in summer, when most of the 38,000 undergrads are absent. However, 10,000 graduate students and 14,000 full time equivalent (FTE) employees remain on campus year-round. Additionally, there are many similarities in occupancy schedules for particular building types and known patterns of building use; with the exception of residences, all involve mainly daytime use. An exhaustive study of residential energy use is only a small component of this study and is left for an additional study at a later date.

A challenge to this study is that in the early years of the green building program, not all buildings attained a similar certification level and some were built only to LEED Silver standards. Of course for non-certified buildings, or for buildings awaiting certification, the final level of achievement is unknown. However, studies have shown that there is little or no correlation between the certification level and energy performance (Menassa et al. 2012; Scofield 2013). No statistically significant relationship between LEED certification level and energy use intensity, or energy saved versus baseline, has been found. Similarly, there is very little correlation between the number of energy credits scored at design time and operational energy consumption (Newsham et al. 2009; Scofield 2009). An important caveat with these studies is that they are based on data derived from buildings certified by earlier versions of LEED. Recent versions of LEED, including LEED 3.0 and LEED v4, have a stronger emphasis on energy efficiency at the design stage and encourage operators to report energy performance. In other words, very recent LEED buildings could be performing better, but the lag time in generating and analyzing data means the improvement may require several years to appear in the literature.

4.4 Methodology

The analysis uses life-cycle assessment to quantify embodied and operational impacts of UBC-V core, and primarily focuses on global warming potential (t.CO_{2eq}) and primary energy (ekWh). For embodied impacts, the model uses the EPA's *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts* (TRACI) to calculate fossil fuel primary energy, stratospheric ozone depletion, acidification, photochemical smog formation, eutrophication and human health respiratory impacts.

For operational impacts, primary energy is calculated from ecoInvent, NTEL, NRCAN and NREL data. The evaluation of GHG impacts, which are contested, is calculated from BC Government emission factors, along with competing values from Hanover & Dowlatabadi (2007) in a sensitivity analysis.

4.4.1 System boundary

The study boundary is restricted to life-cycle energy and material flows in and out of buildings as delimited by their physical site footprints, materials and energy use during each life phase (see Figure 4.1). Site-specific data is shown throughout the study for individual buildings. However, some community scale data is specifically used for context, comparison and benchmarking. Due to lack of data, the impacts of demolition and recycling are not quantified.

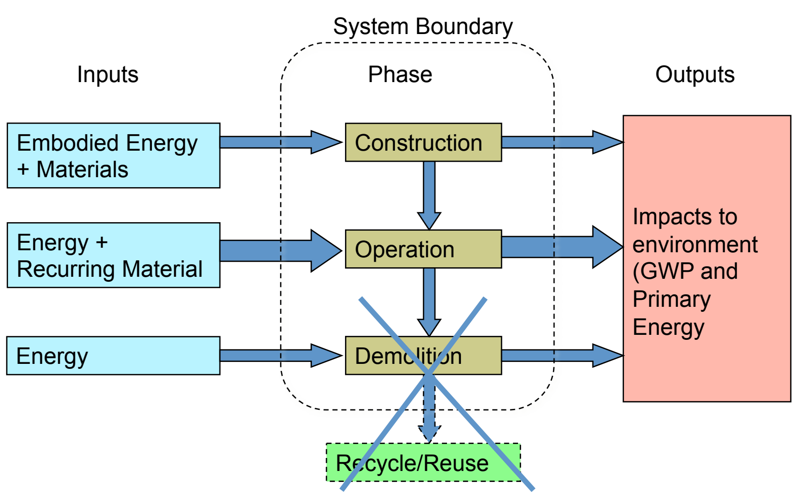

Figure 4.1 System boundary for study. Demolition and recycle/reuse impacts are not calculated due to a lack of data.

4.5 Functional unit

A functional unit is a reference measure for an LCA which provides a comparison point between different systems. At the building scale, the functional unit normalizes impact to building area — specifically *Impacts/m²/year*. At the campus community scale, the functional unit normalizes impact with respect to campus occupancy level — specifically

Impacts/occupant/year. Due to insufficient data resolution for occupancy levels in buildings, the analysis cannot quantify *Impacts/occupant/year* at the granularity of the building scale

4.5.1 Data sources

Impact analysis follows the protocol of ISO 14044 (ISO 2006a) and ISO 14040 (ISO 2006b). Emission factor data is sourced from PAS 2050 (BSI 2008) and BC Hydro. GHG impact calculation is conducted with the IPCC 2007 GWP100 impact characterization method and is summarized in Table 4.1. Embodied impact data is extracted from the UBC-LCA database (unpublished data). Details concerning the database are discussed in Chapter 3 and in Appendix B.

Table 4.1 Data summary for construction and operational phases with sample size N.

Life Phase	**Data Source**	**Model**	**Impact Analysis**
Construction	UBC-LCA database, N=23	Athena EIE	ISO 14044, TRACI
Operational	Pulse Energy/ION metered data, N=80	BEPI study	ISO 14044, TRACI, ecoInvent PAS 2050, NREL, NTEL BC Hydro COeq EF Terasen CO2eq EF IPCC2007 GWP100 Characterization
Deconstruction	N/A	N/A	N/A

Operational metered data was acquired for 12 calendar months from October 2010 to September 2011. A small amount of data was missing in this year due to faulty steam gauges and was imported from the exact same months from the next year. Using

ASHRAE 90.1 methods, this introduces a heating degree day error (HDD) of 3% variation between 2009 and 2011(ASHRAE 2004). Furthermore, there are variations between years, even when weather driven loading is considered. A sample set of eight buildings showed year-on-year variation of 4 - 15%. This means the year-on-year internal consumption variation is much greater than weather dependent HDD variation. The cause of year-on-year variation is not known, but may be attributable to occupancy patterns.

For UBC campus, most heating services are provided by a centralized campus steam plant, while electricity is supplied by BC Hydro. Electricity almost exclusively supports lighting, plug loads and building service loading. However, some limitations to the study exist. A small amount of natural gas is supplied directly to buildings, which contributes to 6% of total primary energy consumption, some of which is used for laboratory processes and cooking rather than heating. This natural gas use is not included in the thermal energy consumption reported in this study because consumption is not metered at the buildings.

Operational energy consumption is converted from site energy to primary energy. For LCA, primary energy calculations must account for the total energy required for extraction from nature. For natural gas, this requires corrections for natural gas extraction, process and delivery. This adds a further 11-21% for well-to-delivery (NTEL 2011; Fulton 2011; Spath & Mann 2000). The variation is due to the quality of natural gas being extracted (sour gas or high CO2 content requires considerably more processing energy). Additionally, extraction processes are evolving rapidly with a shift towards tight gas extraction and higher fugitive methane off-gassing after drilling. A further complication is that the IPCC has recently changed the emission factor for methane meaning the most of the literature requires updating (IPCC 2013). An additional check was conducted using ecoinvent database v2.2 to trace fundamental impacts in sub-process flows. The calculation revealed a value at the lower end of this range, at 11%. Once natural gas is delivered, there are additional losses in the community energy system efficiency for steam delivery. Stantec (2010) has calculated the system to be 62% efficient, including campus distribution losses. The final result is 7.3 MJ/kWh from well to thermal heat, or 48% efficiency when using 11% (overlap between ecoinvent and NREL/NTEL/NRCan range).

Converting electricity site consumption to primary energy requires consideration of grid losses and production losses. The BC Hydro grid efficiency for electricity delivery is approximately 90%. Power production is highly efficient, with large hydro typically in the 90-95% turbine efficiency range (EURELECTRIC 2003). The emission factors (EF) used for energy use at UBC-V are 25 g-CO_{2eq}/kWh (BCGov 2011) and 222 g-CO_{2eq}/kWh of delivered steam. The latter value includes the efficiency of converting natural gas into steam at the UBC steam plant, along with the overall efficiency of the district energy system (overall efficiency of 62%). Various other alternate competing values for the EF of BC Hydro electricity are explored in a sensitivity analysis.

While data for operational impacts is based on available data from 80 buildings, not all buildings are fitted with steam gauges. The thermal data is therefore based on a smaller sample set of 50 buildings. Embodied impacts are available for 23 buildings extracted from the UBC-LCA database.

4.5.2 Uncertainty

Sensitivity analysis is used to probe model uncertainty. There are considerable uncertainties within the proprietary Athena EIE model and data is not available for testing. However, a greater source of variation is attributable to the choice of GWP emission factors. In addition to the BC Government rate of 25 tCO_{2eq}/GWh, two alternate electricity emission factors (84 and 140 tCO_{2eq}/GWh) are tested. These figures are suggested by Dowlatabadi (2007) as being more accurate and take into account, respectively, import/export grid supply dynamics and secondary combustion of waste wood recovered from navigable waterways..

4.6 Results and discussion

Results are split into four sections. The first section is specifically focused on embodied impacts with a focus on GWP. The second section analyses operational impacts and examines the impacts of community scale changes on the building scale.

The third section combines the results of embodied and operational impacts to investigate impact over a 50-year service life. The final section is a sensitivity analysis. Throughout the discussion, the study emphasis is on GWP and energy impacts, both of which are currently the primary concern of UBC.

4.6.1 Section 1: embodied impacts

Data extracted from the UBC-LCA database is used to show the evolution of embodied impacts for UBC-V core buildings constructed from 1912 to 2011.

4.6.2 Embodied Carbon

The curve in Figure 4.2 shows increasing carbon intensity per unit area over time. UBC-V's first buildings, constructed in the 1920s, were wood-framed. These older buildings show the lowest embodied effects (average 0.16 $t.CO_{2eq}/m^2$ from 1920-48). Buildings with the highest embodied GWP are from the 1960-2000 period, with an average intensity of 0.26 $t.CO_{2eq}/m^2$. This latter construction phase is dominated by the extensive use of structural concrete and is close to figures reported by Ochensendorf (2011) of 0.21 $t.CO_{2eq}/m^2$ for concrete buildings (Ochsendorf et al. 2011). As cement is one of the main drivers of embodied energy and carbon impacts, the increasing structural concrete content has caused an approximately two-fold increase in embodied GWP over time. This data does not include credit for 'stored' carbon in the buildings. This would further reduce the total embodied impact, but depends on land-use change and the final fate of wood products after building demolition (Nässén et al. 2012; Gustavsson & Sathre 2006). Forestry extraction practices, end-of-life product re-use, landfilling and incineration all have an influence on calculating the scale of a carbon 'credit'. Studies with applicable and reproducible carbon accounting methods remain elusive and benchmarks are at a nascent stage, with most analyses conducted at an individual or pairwise scale. LCA differences between wood and concrete have been reported at 0.11 and 0.47 $t.CO_{2eq}/m^2$, respectively for 1200m^2 4-storey buildings (Gustavsson et al. 2006). Robertson (2012) reports 0.126 $t.CO_{2eq}/m^2$ for timber buildings with structural wood counted as a storage credit (Robertson et al. 2012). Page (2006) report 0.149 $t.CO_{2eq}/m^2$ without storage credit (Page 2006). Concrete buildings have been found to embody higher levels of GWP with 0.33 $t.CO_{2eq}/m^2$ reported by (Fernandez 2008), 0.64 $t.CO_{2eq}/m^2$ (Suzuki & Oka 1998) and 0.369 $t.CO_{2eq}/m^2$ (Page 2006). The UBC LCA database wood-concrete range is comparable at 0.16 - 0.30 $t.CO_{2eq}/m^2$. Further details and data are available on the UBC-LCA database in Appendix B.2.

There is no observable post-2000 improvement in embodied carbon for LEED buildings. This was unexpected, because the rating system encourages the use of lower impact materials such as fly ash in concrete and local materials. Using 25% fly ash substitution for cement in concrete lowers embodied GWP of the concrete by 15.1% (Ochsendorf et al. 2011). However, these benefits are not observable in the UBC data. The difficulty in aligning LEED measures with measurable improvements is well known. Scheuer and Keoleian (2002) examined individual LEED credits in LEED 2.0 with respect to life-cycle efficiency. They show that a focus on cost-based energy calculations does not always enhance actual and measurable environmental improvements. Additionally, they find that Materials & Resources (MR) specifications on local materials are similarly unhelpful, since transportation impacts are a relatively small contributor to total impact (Scheuer & Keoleian 2002). Figure 4.2 shows the results for the CIRS building which, as discussed, involves extensive use of wood to offset for carbon (calculation details in Chapter 3). CIRS utilizes over 500 m^3 of softwood within the columns, beams and floors which, based on 0.76 $t.COeq/m^3$ (see Chapter 3), brings the embodied carbon intensity down, from 0.21 t.CO_{2eq}/m^2 to ~0.08 t.CO_{2eq}/m^2 after a credit for carbon storage is applied. With the exception of the earliest buildings, most UBC academic buildings use very little structural wood and receive negligible carbon 'credits'. The result is that the Regenerative building is ~70% below the GWP 1960-2000 average and has the lowest embodied GWP of any building since the 1920s.

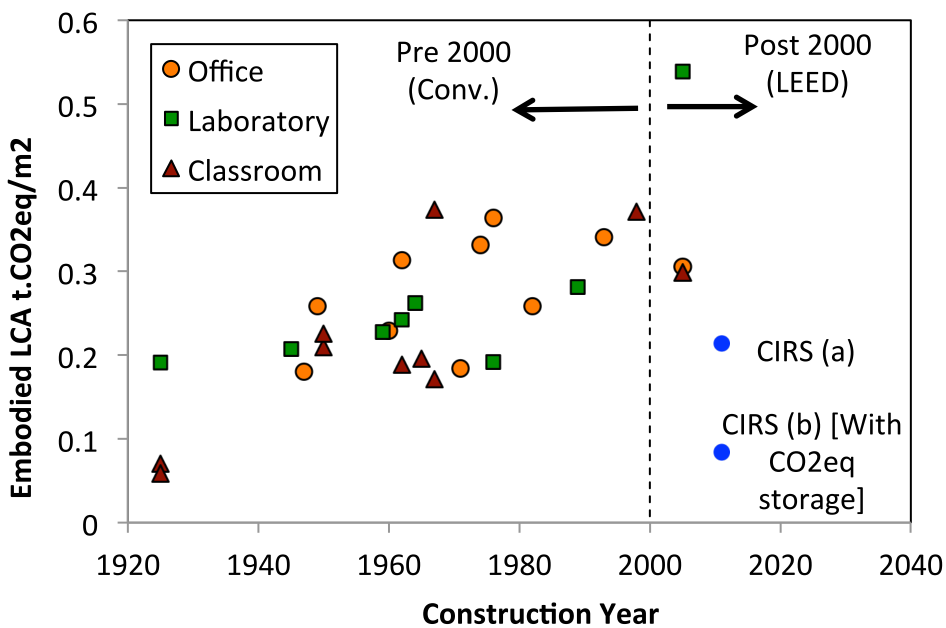

Figure 4.2 Embodied GWP impacts for buildings constructed 1920-2011.
The Current Trends line shows the approximate 'no-change' expected embodied content of CO2eq. The Target line shows the aspirational embodied CO2eq for new construction (embodied carbon neutral by 2050). CIRS (a) is the GWP with no credit given for CO2eq storage. CIRS (b) is with credit.

Additional large-scale wooden buildings have recently been constructed, such as the Earth Sciences Building, although analysis has not yet been completed to determine overall embodied carbon balances. While the use of wood assists CIRS to get close to carbon neutrality, more data is required to determine if widespread use of wood will enable UBC-V to achieve carbon neutrality for a larger, community scale.

Finally, it is worth noting that there are many variables driving the evolution of impacts over time. These include, but are not limited to, the evolution of building codes (improved seismic performance), the recent uptake in the use of large atria for ventilation, the increasing use of windows and aluminum framing, and others. Further research could be conducted for multi-regression analysis on material types, prevalence and impacts (as embedded in the Athena database).

4.6.3 Embodied primary energy impacts

The embodied energy for UBC-V campus buildings shows a similar trend over time as found for embodied carbon and indicates a rise over time due to use of concrete (data not shown). The reason is the same as the driver for embodied carbon, the coupling to the increased use of concrete. The UBC-LCA database shows an average embodied energy of 937kWh/m^2 for 1960 - 2000 buildings. While there are few studies for embodied carbon, benchmarks are being developed for embodied energy. A large meta-survey from eight literature sources containing 18 individual process LCA studies of multi-storey buildings shows an average embodied energy of 861kWh/m^2/lifetime (Nässén et al. 2007). This is 17.2 kWh/m^2/yr when annualized over 50 years, which is within 10% of the UBC-LCA campus average of 18.5 kWh/m^2/yr. By comparison, France's *Centre Scientifique et Technique du Bâtiment* (CSTB), with 74 mixed-age buildings analyzed, reports 35.9 kWh/m^2/yr embodied primary energy annualized over 50 years (Levaux, 2011). The mismatch is at least in part due to UBC-LCA using the gross building area (total area), whereas CSTB is using SHON (net livable area). Caution must be taken with regards to comparing the UBC-V averages against external benchmarks, due to differing methodologies and regional assumptions found in each study, along with variations in material and energy intensities. Further meta-study analysis would enable formal harmonization of system boundaries and correction for methodological differences.

Figure 4.3 shows the remaining environmental indicators as defined and calculated according to the TRACI LCIA scheme. The base-case comparison is the UBC-LCA database average, which is the community-wide mean, based on 29 individual LCA studies. Impacts are plotted with respect to two sample building types: offices and laboratories.

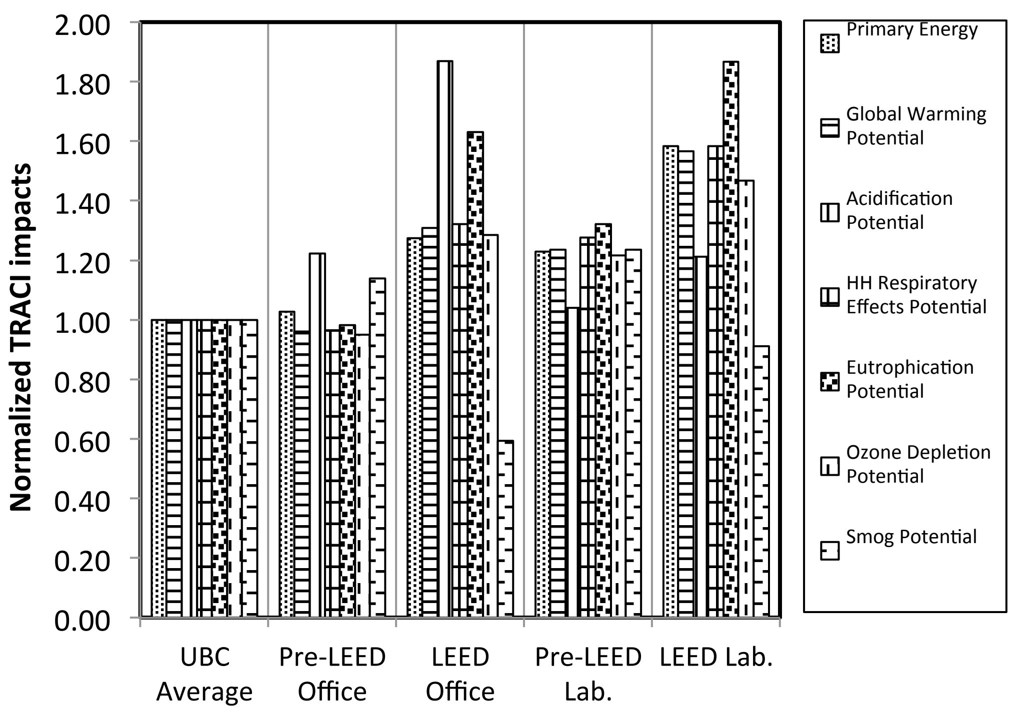

Figure 4.3 Embodied GWP TRACI impacts for buildings constructed 1920 - 2011, showing comparison of pre-2000 and post-2000 for offices and laboratories.

The impacts for laboratories are higher than for offices for most environmental categories. This reflects the intensive structural provision and requirements for laboratories, as compared to offices, which are relatively less materially intensive, especially in terms of concrete use. Post-2000 buildings have higher impacts across most metrics, with 18-25% increases over Pre-2000 buildings for both offices and laboratories. This difference is likely due to the increasing intensity of concrete use, cancelling out gains by the uptake of fly ash in LEED.

4.6.4 Section 2: Operational impacts

Operational impacts are based on monthly-metered data acquired for 80 buildings monitored by ION meters. The metering includes site thermal consumption (steam gauges) and electrical usage. LCA methodology requires that all site values are first converted to primary (source) energy using conversion factors of 1:2.1 for steam and 1:1.1 for electrical usage (Stantec, 2010; BC Hydro, 2010). Site data are presented for comparison to external survey data and targets issues by NRCAN, RealPac and BOMA.

To provide context for this section of the analysis, a summary of UBC-V building energy management strategies is provided. UBC-V has engaged in an aggressive program of demand-side energy management starting in 2001 with the six-year CDN$39m ECOTrek retrofit project which, as mentioned, reduced emissions intensity by an estimated 24%. ECOTrek, the largest energy and water retrofit project on any Canadian campus at that time, upgraded 288 academic buildings, as well as the steam system.

UBC-V expects to improve steadily over the next 10 years. Future emissions reductions will be attained with supply-side strategies: the Bioenergy Research and Demonstration Facility (9% emission reduction) and the Steam to Hot water conversion (22% reduction), along with the Continuous Optimization retro-commissioning program are anticipated to produce a further 10% reduction on the demand side. Together these three projects will achieve the 2015 target of 33% reduction compared to the 2007 baseline, achieved during a period of rapid growth for the campus. With buildings and the district energy system representing 97% of total campus emissions, these strategies are beneficial for reducing whole-campus emissions. The forecast improvements in the efficiency of thermal delivery (upgraded steam to hot water conversion) are analyzed later in the sensitivity analysis.

4.6.5 Operational GWP impacts

Figure 4.4 shows the total aggregated consumption for the data set with respect to the year-of-construction, for historical emissions for electricity and steam CO_{2eq}. The overall trends are a first-order approximation based on recent individual building operational performance. Here it is assumed that, in the absence of building retrofits and upgrades, building performance has remained relatively static since construction. We also assume that the greenhouse gas intensity of BC Hydro electrical supply, and UBC-V steam generation have improved only slightly or remained steady; since 1990, GHG intensity for the commercial/institutional sectors decreased slightly by 5% (Nyboer et al. 2011). Very little is known about pre-1990s emissions; hence the level of error for 1920-1990 is large. The future trends are also problematic in that the actual system efficiency will likely deviate from predictive models due to possible restructuring of British Columbia natural gas supply, export and electrical generation.

The results show that emissions have risen rapidly since 1962, with a marked acceleration since 2003, in part due to a surge in new construction. Overall, UBC-V has 41% of committed reductions in place to reach the 2015 target of 33%. The committed curve shows the results of current strategies already in place, giving reductions until 2030. However, there remains a CO_{2eq} reduction 'gap' of over 17,600 t.CO_{2eq}/year by 2050 which remains a challenge. This gap gives an estimate of the deficit to be closed by demand control strategies.

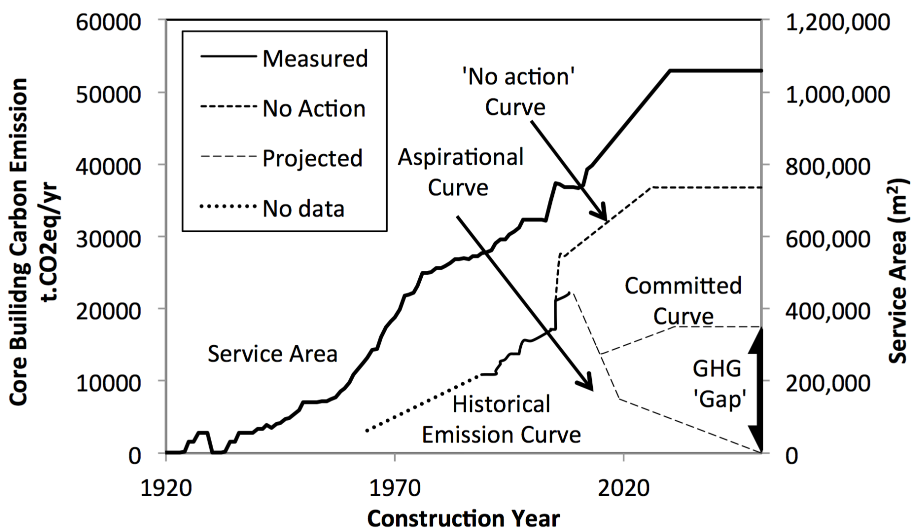

Figure 4.4: Operational carbon impacts for buildings constructed 1920-2011.
The curve represents the yearly combined historical operational emissions for the UBC-V core building stock. The 'No actions Curve' line shows the approximate expected CO2eq without any energy efficiency strategies (no ECOtrek). The 'Aspiration Curve' shows the target CO2eq for campus building operations.

Demand side control is expected to be influenced by the building densification policy at UBC. Densification at UBC-V is coupled with the renewal cycle and involves replacing demolished buildings. If these new buildings are more efficient, demand is reduced. However, many of these older buildings scheduled for demolition have relatively small process loads, and hence have low levels of energy consumption. The replacement buildings often have more intense loading, so strict energy limits for all new construction will be required to prevent overall energy demand inflation. Overall, there is an increase in floor space due to increasing building heights. The total demolition of core buildings from 2011-2020 will be 50,000 m^2, whereas the new building area will be 133,000 m^2, giving a net increase of 83,000 m^2 (C&CP 2009). All of this new construction is scheduled to be built to LEED equivalent standards, which further motivates careful operational analysis to examine LEED's ability to reduce the GHG 'gap'.

Error! Reference source not found. shows CO_{2eq} emission variation with respect to building type. The extreme values embedded in the data group, coupled with small sample sizes, indicate that the median, not the mean, is an appropriate statistical measure. The relative contribution of CO_{2eq} for thermal and steam heat is shown for five building types. Due to British Columbia's low emission factor for electricity (emission factor of 25 t.CO_{2eq}/GWh), the electrical impacts are an order of magnitude lower than those due to natural gas combustion for steam heat. An analysis for a higher emission factor is shown later in a sensitivity analysis.

Differences with respect to building types are observable, which is expected, but variation within each group is high due to unknown plug loading and patterns of occupation. The emissions for thermal heat provision dominate, with laboratories showing over 90-180% excess over other building types. LEED equivalent buildings can be seen scattered across each distribution, with no clear upward or downward improvement. The newer LEED buildings would be expected to operate more efficiently due to higher standards of construction. However, this is not apparent in the data.

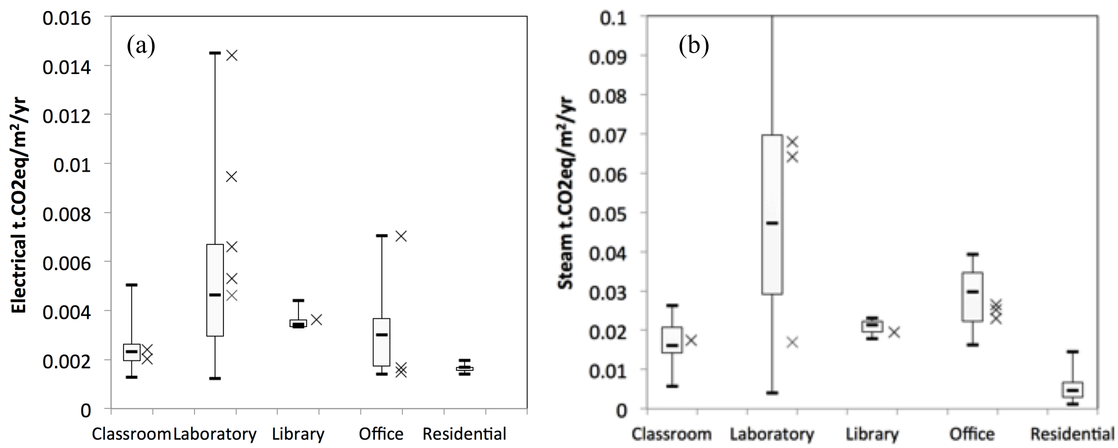

Figure 4.5: Site operational GWP for UBC-V buildings from metered data normalized by area. Shows CO2eq emissions for (a) electrical consumption and (b) steam heat. The central band is the median. Upper and lower extremities mark the limits of values outside the quartile ranges. 'x' indicate LEED equivalent buildings.

Problematically, all building types except residences show large variation. If performance of the scheduled 83,000 m^2 of new building stock expansion continues with this same amount of variation, then UBC-V will not be able to rely on LEED certification of its buildings to provide demand reductions and contribute to carbon neutrality by 2050.

4.7 Operational energy performance

Operational energy data is analysed with respect to the LCA methodology, which requires conversion to primary energy. In contrast, most institutions, including UBC operations, conduct analysis from a site-use aspect. For completeness, both are reported. A statistical ambiguity is often overlooked with energy surveys, in that averages are reported without due attention to median values. As Schofield (2009) has reported, a few large buildings can skew averages upwards (or downwards) while leaving median values preserved (Scofield 2009). Figure 4.6 shows how UBC office[5] buildings compare against both median and mean values. In this particular case, the median and mean are close in value, which is a statistical coincidence. A close look at office performance in Figure 4.7(b) shows that the asymmetrical quartiles in thermal and electrical usage 'cancel' each other out.

Overall, UBC building performance compares similarly to other buildings off-campus and is at least in the expected range of performance.

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[5] Office buildings are selected over other building types because of widespread reporting. External survey results for non-office buildings are less commonly reported.

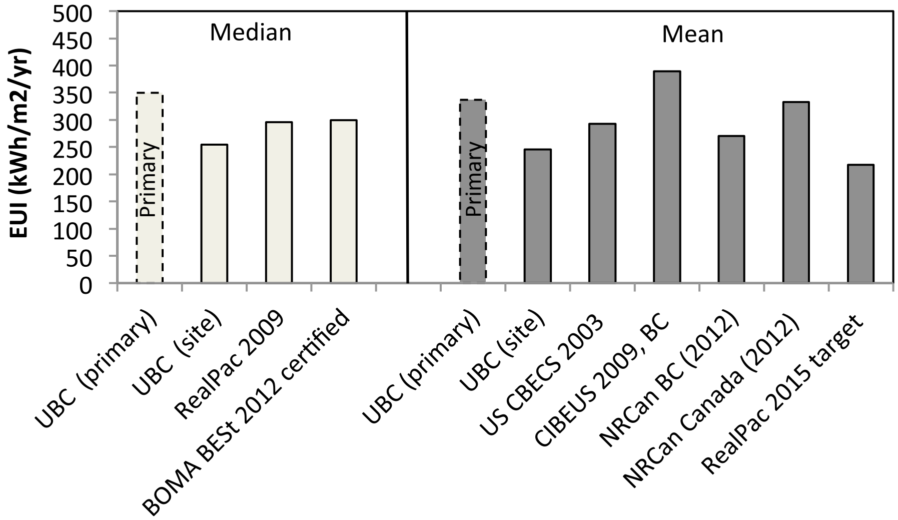

Figure 4.6: Total site energy consumption for UBC-V office buildings 2009-2010, normalized by area. Primary energy is shown for comparison.

Disaggregation of the above data with respect to year of construction reveals further variation as is shown in Appendix C.3. The results show that despite improvements in building technologies over the past 80 years, consistent improvements in energy efficiency have been stubbornly difficult to attain. Other energy study surveys report similar lack of progress. For example, CIBEUS commercial office energy survey results for buildings constructed in the period from 1920 – 2000 show that energy consumption remains remarkably unchanged over multi-decadal periods of time (NRCan 2005).

Figure 4.7 shows energy consumption with respect to LEED, versus older non-LEED buildings. LEED equivalent buildings are shown as individual ‘x’ points overlaid on top of the conventional building performance distributions. The upper extremes for both LEED and conventional are often far in excess of the quartile bands, which is problematic in determining trends. An alternate data visualization is shown in Appendix

C.4, which shows the energy performance of buildings ranked in ascending order; again LEED buildings are scattered through the rankings. The variability in energy performance is not confined to LEED, but has been similarly reported in a 4,000 building survey of non-residential New York City buildings, and recently for BC buildings (NYC Citywide Administrative Services 2011; Casavant 2013).

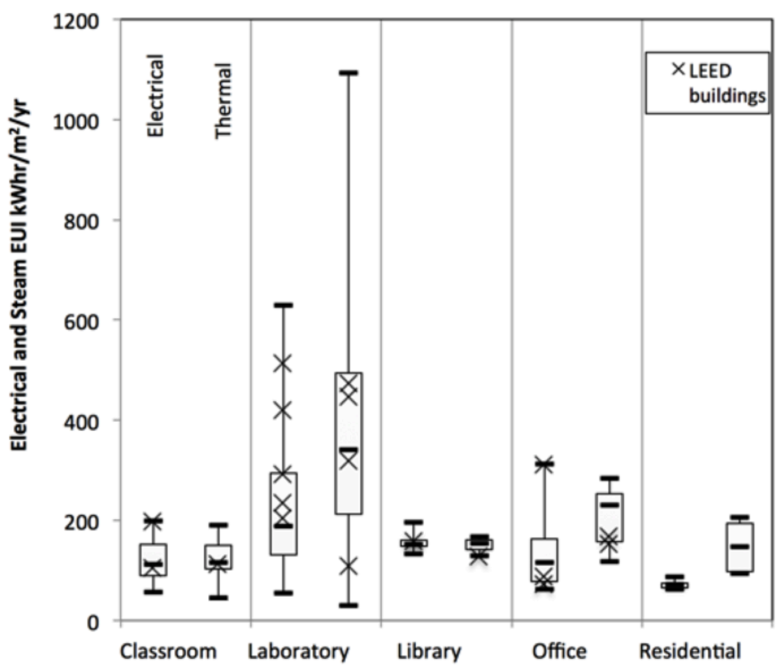

Figure 4.7: Operational primary energy consumption for UBC-V buildings from metered data 2010-2011 showing primary electrical data and steam heat data.

Other correlation attempts:

In order to determine whether building morphology was a driver in energy consumption, a correlation search between building surface-to-volume ratio and energy consumption was undertaken. It was expected that, if the ratio was small and the buildings were compact, then efficiency due to a minimization of thermal loss through envelopes would show energy savings (Pessenlehner & Mahdavi 2003; Ratti et al. 2005). An extensive regression analysis of aerial LiDAR radar data, which reveals the building morphology of UBC-V buildings, showed no correlation with thermal energy consumption. This failure does not dispute the importance of building morphology for determining thermal performance, simply that the morphology signal is too small to be measured when compared to other driving factors such as occupancy and plug-load variation. Similar, exhaustive studies looking for correlations with respect to operational schedules (building opening hours) and occupancy schedules failed to reveal any correlations.

4.7.1 The influence of ASHRAE energy standards

While the results show the performance of LEED, they are also a measure of the efficacy of embedded ASHRAE 90.1 and MNECB energy standards that are used to provide baselines during design phase energy modeling process. These standards have become incrementally more stringent over time. Figure 4.8 shows the evolution over time for both standards, starting with ASHRAE 90-75, through to 90.1-1980, 1989, 1999 (basis for LEED 2.1 and LEED Canada) 2004, 2007 (basis for LEED 2009) and 2010, to the projected performance of 90.1-2013 (Halverson 2010; Thornton et al. 2011). The Model National Energy Code of Canada for Buildings is shown for NECB 2011 which is 25% better than MNECB 1997 (Caneta Research 2010; Hepting n.d.) whereas ASHRAE 189.1-2009 standard is 30% better than ASHRAE 90.1-2004 (NREL 2010). ASHRAE 189.1 2011 is 30% better than 90.1-2007. The trend for improved energy performance should have yielded approximately 62% in accumulated energy savings. A challenging question is to ask why the mandated energy savings are not visible in the UBC survey data. There are many reasons for this, in part because MNECB 1997 was not broadly implemented and ASHRAE 90.4-2004 was not included in the provincial code until 2008[6].

While there is a time lag between the arrival of a revised standard and its implementation, it would be expected that the arrival of LEED should have ushered in the required ASHRAE improvements in the UBC data for all building types in the 2000s. However, this is not yet observable in our data. A possible cause is that the early versions of LEED were less stringent about ensuring energy improvements. Fortunately, recent versions of LEED contain more challenging energy prerequisite points, which will hopefully improve energy performance in the future.

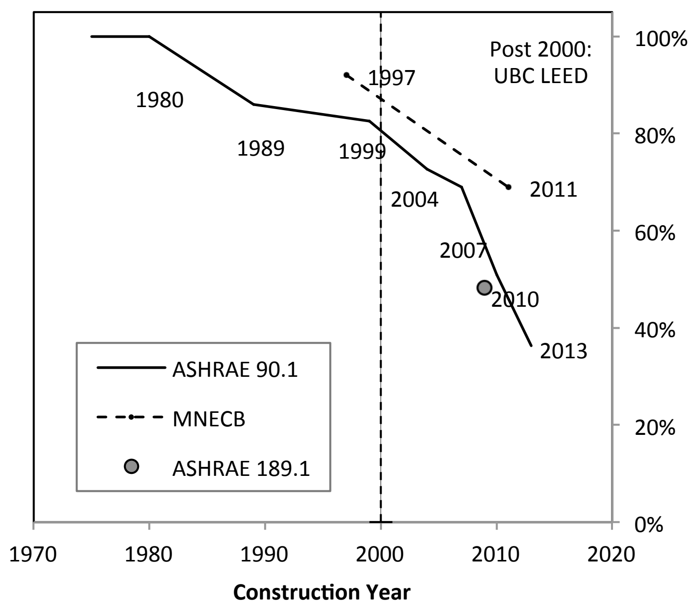

Figure 4.8: The evolution of ASHRAE and MNECB standards is shown with respect to a percentage gain over the early versions of ASHRAE.

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[6] However, more recently there has been a rapid infusion of standards being centralized into codes (NEB 2008). The City of Vancouver is an example of an early adopter and has been consistently ahead of the curve by several years. The city is currently using ASHRAE 90.1-2007, and will be using ASHRAE 90.1-2010 by 2013, and it will be interesting to analyze future performance data after this new energy standard is implemented. Note, that UBC-V is not part of the City of Vancouver.

4.7.2 Building stock evolution at the community scale

For most municipalities and large institutions, energy improvement interventions have focused on the building scale. This approach limits a solution space to building footprints, when greater gains may become available by looking for synergies at the community scale. This is supported by (Retzlaff 2009), who suggests that bridging the gap between community planners and building designers is a path forward. In order to better understand the building scale challenges to energy performance, the influence of the community scale dynamics are explored with UBC campus data. The UBC building stock has evolved considerably over the decades, and extensive institutional archival records enable an exploration of long-term community scale changes. Figure 4.9(a) shows the evolution of programming space over time for UBC-V core campus buildings (core campus is here defined as large buildings used extensively for academic research, administration and classroom programming). The post-WW2 period shows a strong commitment to creating library and classroom areas. More recent trends show a steady reduction of library space and an increase in laboratory area. Effectively, this means that low-energy intensive-use areas have given way to high-energy intensive use. This finding links community scale use changes to energy utilization at the building scale.

Recontextualizing energy-use based on population intensity allows a different view. Figure 4.9 (b) shows the historical trend in student full-time enrolment (FTE) per unit area, which is a reasonable proxy for building occupancy. The data shows a decline in FTE occupant density from the crowded years of the 1950s to a low-density campus in

1996. Recent trends to the present day show a slow return to higher levels of occupant density and indicate that enrolment is beginning to outpace new construction. Figure 4.9(b) also shows that absolute electrical consumption (only available from 1992) has increased in recent times. By evaluating the two trends together, energy intensity per capita can be approximated. If levels of occupancy are rising faster, or slower, than yearly changes of energy consumption, then use per person becomes an interesting metric for progress.

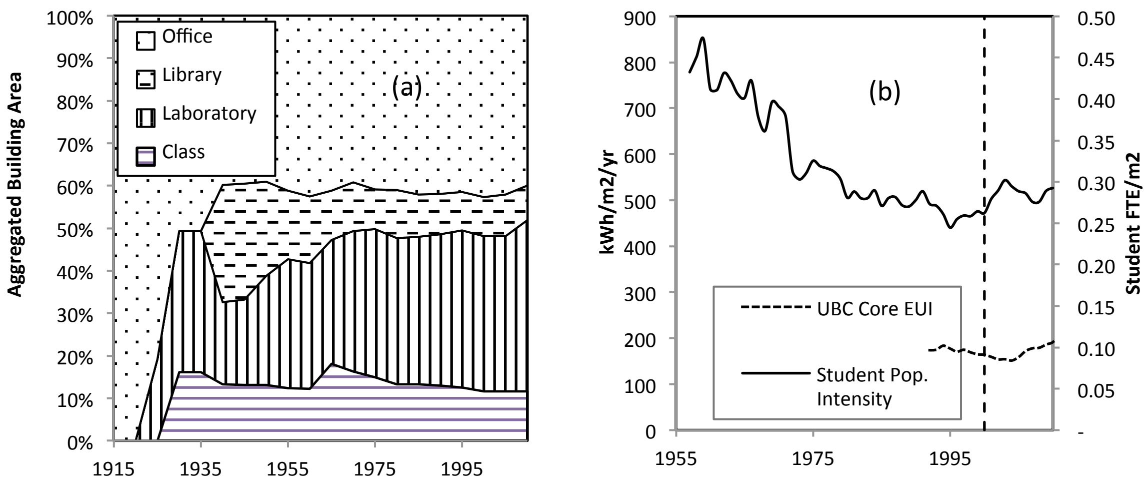

Figure 4.9: Community scale changes over time.
Chart (a) shows how the building programming has evolved using aggregated data from sub-building scale records of use and (b) show student FTE enrollment data and community scale energy trends since 1992. 'Core' building area represents main academic buildings, not ancillary buildings such as the TRIUMF facility.

Figure 4.10 zooms in on the recent period of time shown in Figure 4.9, from 1992 to 2011:

- Figure 4.10(a) shows that, over this 19-year span, absolute core-campus electrical consumption has increased by ~35%, and thermal consumption has varied and shows a small recent improvement of ~5-15%. Electrical increases are likely due to increased process and plug loading.

- Campus energy consumption normalized to utility service area shows electrical use has increased by 11% and steam use has declined by 20-30% (data not shown). This means that the provision of thermal energy services per square meter has improved over time, possibly due to improved efficiencies in steam delivery to an increasingly dense core of buildings. Additionally, thermal waste from increasing electrical loads could be offsetting some thermal heating in winter although, unfortunately, this effect cannot be derived directly from the data.
- Figure 4.10(b) shows that, from a per capita viewpoint, electrical consumption has held steady, but that overall total steam consumption per person has declined by a large amount of 30-40%. This shows that occupants are using utility services more efficiently due to recent increases in occupant density.

In summary, large improvements are observable for energy consumption when normalized by campus occupant FTE. This finding suggests that reporting energy use per person could be a useful additional metric for guiding policy. Ensuring high levels of occupancy for campus buildings will improve per-capita performance, while housing the same number of occupants in fewer square meters would improve absolute levels of energy usage, though care must be taken to address issues of crowding and functionality.

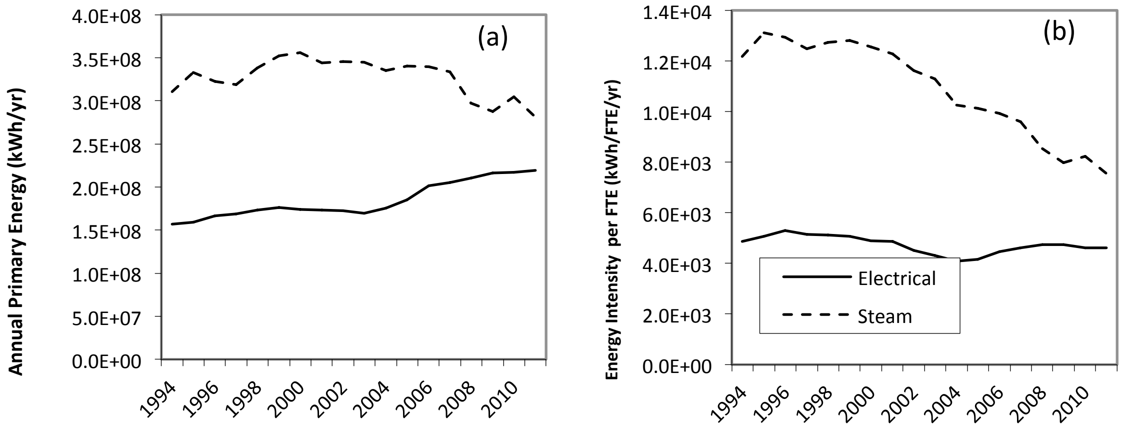

Figure 4.10: Community energy scale trends.
Chart (a) shows absolute community scale (core building) steam and electrical consumption. Chart (b) shows the energy use per student (full time equivalent FTE).

4.7.3 Section 3: Integrating embodied and operational impacts

Understanding the relative contribution of impacts throughout the life-cycle is useful for gaining insight into where mitigation strategies will have most leverage. Figure 4.11 shows the combined embodied and operational TRACI impacts over a future projected service period of 50 years. As expected, the bulk of primary energy and GWP impacts is clustered in the operational phase (88% and 96%). This has been found in previous work. (Cole & Kernan 1996; Robertson et al. 2012; Guggemos & Horvath 2005) report 89–98%), (Scheuer et al. 2003) report 83%, and (Rossi et al. 2012) report 85-92% for residential buildings.

However, for other environmental categories, the relationship between embodied and operational impacts is more complicated and the relative ratio varies according to impact category. For several categories, embodied impacts are on par with operational impacts.

For LEED office buildings, TRACI respiratory and eutrophication impacts are slightly higher than operational impacts. Moreover, as operational performance improves, as expected for net-zero and Regenerative buildings, it is expected that the ratio of embodied to operational impact will become more significantly weighted towards construction impacts (Blengini & Di Carlo 2010).

In summary, a large share of GWP and primary impacts is attributable to operational impacts as reported in the literature, and is recovered by the model. When other environment metrics are considered, the relationships are more complicated. If stakeholders are concerned with more than just GWP simplistic footprinting, then LCA can be used to gain more insight.

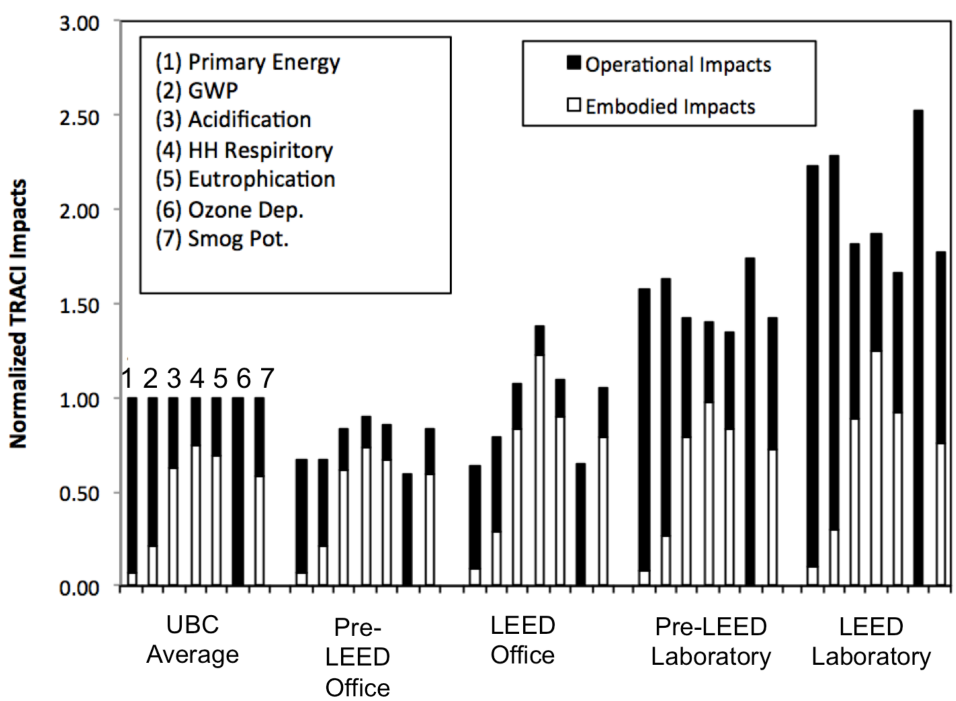

Figure 4.11: Combined operational and embodied TRACI LCIA data for offices and laboratories. For reasons internal to the Athena EIE model, embodied ozone depletion rates are unusually low.

4.8 Sensitivity analysis

The characterization of GWP emission factors of BC electricity generation is contested. As stated, the value used in the model is 25 tCO_{2eq}/GWh. Dowlatabadi (2011) suggests that this should be increased to 84 tCO_{2eq}/GWh, to account for interprovincial night imports (Dowlatabadi 2011). A further upper bound of 140 tCO_2e/GWH is suggested for the inclusion of regional burning of wood cleared from navigable waterways (Dowlatabadi 2011). The sensitivity result for the upper value is shown in Figure 4.12. For the extreme high value of 140 tCO_2e/GWH, electrical emissions can match thermal emissions for non-laboratory buildings. The result is less sensitive for laboratory buildings, due to the disproportionately large amount of thermal energy provision (relative to electrical services) due to venting conditioned air.

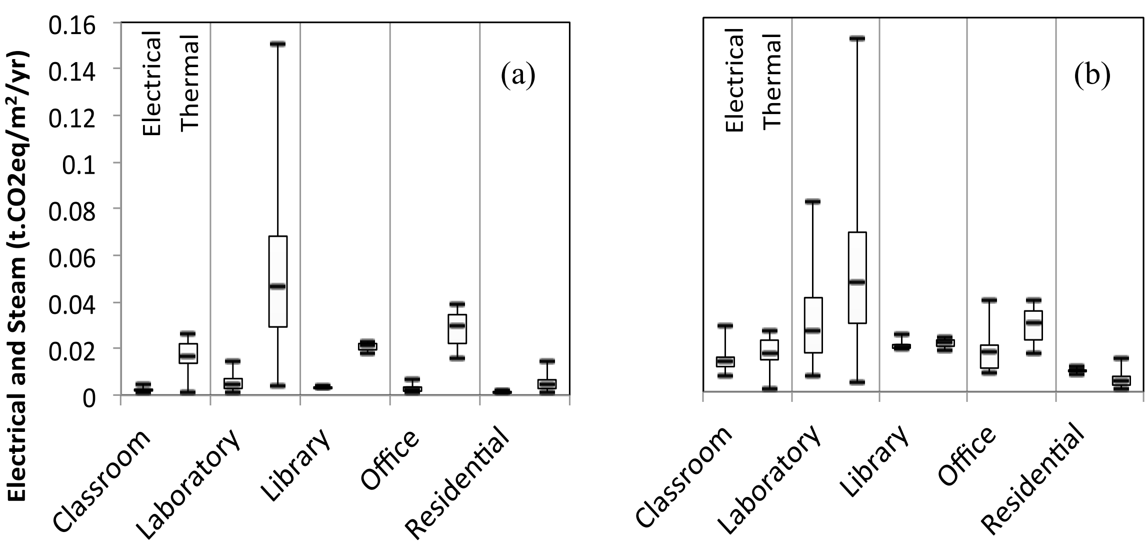

Figure 4.12: Sensitivity test for GWP. Chart (a) shows results for 25 tCO_{2eq}/GWh .(b) shows results for 140 tCO2e/GWH.

When the campus hot water loop upgrade becomes active, 22% further efficiency gains for thermal heat provision will be realized. This further closes the gap between electrical and natural gas emissions and, in the case for an EF of 140 tCO_2e/GWH for hydro power, this means that classrooms, libraries and residences could potentially have higher GWP from electricity.

4.9 Conclusions

Life-cycle analysis is used to compare the embodied and operational environmental impacts of 10 LEED buildings against 70 conventional buildings over nine decades of construction history:

- Construction phase impacts, embodied energy and GWP of UBC-V buildings are found to be coupled to construction year. Embodied impacts have risen steadily over time, primarily due to the increasing use of structural concrete.
- Operational energy performances of UBC-V buildings are highly variable. In contrast to the embodied trend, building age was found to have very little influence on energy consumption. There is no significant trend in energy performance improvement for buildings constructed from 1920 - 2010. The source of variation was not observable in the data. Additionally, energy performance was found to be uncorrelated with building morphology.
- LEED building energy performance is similarly highly variable, with no statistical improvement over conventional buildings. UBC LEED and LEED equivalent buildings, as constructed from 2000 – 2011, afford no guarantee of improvement over conventional buildings.

- Understanding community scale changes in terms of population intensity are important for contextualizing the building scale dynamics. Increases in campus population density reveal that performance can be observed to improve when impact is normalized to per-capita metrics.
- Combining operational and construction impacts over a 50-year service life shows that conventional metrics, such as primary energy and GWP, are mainly attributable to operation, which is in agreement with the literature. However, analyzing other impact categories shows that embodied impacts compete with operational impacts. If stakeholders are only concerned with minimizing GWP, then focusing on operational impacts is a sufficient strategy. If other impact categories are of concern, then paying greater attention to construction materials would be prudent.
- With regards to uncertainty, the model is quite susceptible to the emission factor for electrical generation. In the case of high emission factors, electrical consumption should be minimized, and any thermal provision directly via electricity should be avoided.

Future research is required to determine the cause of operational variation. The lack of improvement by recent buildings cannot be pinpointed as a problem exclusive to LEED practices. Standards underpinning LEED, such as ASHRAE 90.1 energy code, are not producing expected reductions. Other operational drivers associated with occupant use, such as plug loading and HVAC services, need further investigation.

Chapter 5: Conclusion

5.1 Overview:

The research findings in this dissertation contribute to a broader, life-cycle contextualization of performance evaluation for buildings. The research shows that the focus on up-front impacts, which is the current emphasis of most building evaluation assessments such as LEED, leads to an incomplete description of the complexity and tradeoffs of impacts over time. With respect to the main objective of this dissertation, which was to identify life-cycle dynamics between different approaches to 'green' buildings, this research illuminates how design decisions lead to a wide diversity of outcomes that are horizontally interlinked with other building systems, or vertically coupled to supply chains. The findings indicate that effective decisions are facilitated by adopting a systems' approach to life-cycle assessment, to mitigate both recurring and continuous impacts and to use life-cycle benchmarks for tracking progress over time.

The research objectives were achieved through the integration of multiple LCA models representing small scale systems inside buildings, building scale systems and large community scale systems. This integrated approach links together isolated models to produce a useful, more connected, data map of overall performance and to provide high quality and interactive knowledge for decision-makers. The research enables designers, owners and operators to understand that the different stages of a building life-cycle are intimately connected, by financial and environmental outcomes, to their design and operational decisions. The different consequences of these decisions are also interconnected, yet separated by intra-institutional barriers and by inter-generational discontinuities. This concluding chapter provides a summary of how a life-cycle ‘lens’ can reveal these relationships and how stakeholder participation can provide insight for performance-based sustainability. Finally, the chapter closes with policy implications with respect to approaches to benchmarking, mitigation of risk, the identification of co-benefits and a discussion of future research direction and topics. This chapter first revisits each research objective in terms of its attainment, and discusses findings along with study limitations and recommendations for future research and model improvement.

The four research objectives, outlined in the introduction to section 1.9, were motivated by the need to understand the relative life-cycle impacts of design decisions at each life-cycle stage. The following discussion examines how each objective was met, in terms of the themes outlined in the introduction; namely, reactions to internal and external drivers of changes, and uncertainty and use to decision-makers.

5.1.1 Objective 1

The first objective was to use a case-study to compare the financial performance of LEED Gold against a Regenerative building:

> *“What are life-cycle cost impacts of a building constructed to CIRS ‘standard’ compared to LEED Gold? “*

The LCC study (Chapter 2) connects financial impacts across a case-study building life-cycle in terms of budget responsibility, not only across intergenerational spans of time, but also between stakeholders, often with contrasting priorities. The findings show that the first cost premium of CIRS is 28% more than a regression average of comparable

UBC buildings; however, more significantly, CIRS is within two standard deviations of the mean (which describes the extent of statistical variation within the 95% percentile limits). This is significant because it indicates that, despite its advanced structural and environmental technologies, CIRS is within the range of expected costs. The technical challenge of constructing one of the first large timber-framed buildings in British Columbia was non-trivial. The wood structure of CIRS is estimated to have increased the cost of CIRS by $0.5-0.75M. Additional contributing factors are discussed, including the effect of high ceilings in CIRS, which meant that the total useable floor area was less than other buildings with the same volumes but with lower ceiling heights.

The model shows that the CIRS cost premium can potentially be recovered after 20.5 years of design-intent performance. However, the model also reveals energy cost burdens due to poorly commissioned systems and design errors. With the building currently, at the time of writing, being unable to realize the energy design intent, the cost of inaction could add up to 4 years to the pay-back time of the building. Non-rigourous commissioning has meant that an improperly installed heat exchange system has been transferred from developer to operator. This commissioning failure is particularly surprising within the context of the case-study building which is owner-operated. In this case, the inability to deliver a functioning building shows that failure is institutional as well as technical. The barriers to attaining aspirational performance are multi-dimensional and discussed in detail by Fedoruk (2013).

The perspective given by the life-cycle costing models is useful for exploring budget responsibility and risk for stakeholders. The total cost of ownership at UBC, from a 'budget responsibility' point of view, is split between procurement, which is managed by UBC Properties Trust (UBCPT), and operations, which is managed by UBC Infrastructure Development and UBC Operations. After 50 years of operation, the budget burden is split 75:25 and 60:40 (depending on the discount rate). UBCPT has responsibility for managing the project budget. Ultimately, they report to the Vice President – Finance, Resources and Operations through the Infrastructure Development division, but in practice, they have a good deal of operational independence. However UBC Infrastructure development and UBC Operations are ultimately responsible for operational issues. Both stakeholders have a large stake in the overall budget, but are separated by institutional barriers. The contrasting financial priorities mean that budgetary concerns, especially over the long term, are hard to align.

The model showed that the financial management in the development phase, which is overwhelmingly dominated by construction cost control, is highly sensitive to exogenous variables such as escalation rates, and to endogenous variables such as discount rates. For the former, a sensitivity analysis reveals that small incremental changes in construction escalation cost can have a disproportionately high impact on the total cost of ownership. For the latter, the choice of discount rates profoundly influences expected first-cost investment pay-back times. "The model used the Ministry of Advanced Education discount rate of 5.2% real (7.2% nominal) which is required for all BC educational building planning. The AVED rate yields a payback of 20.5 years. However, sensitivity analysis show that the use of low social discount rates instead of higher market rates decreases pay-back time by 2.2 years. This is not to suggest that the social discount rate be used, rather, the point is to illuminate that the selection of an appropriate rate is important in terms of modeling.. Conversely, real rates of above 7.2% will result in the first-cost investment never being paid off. The choice of appropriate discount rate is an intrinsic component of any life-cycle costing and requires careful interpretation, especially with regards to evaluating sustainability related performance gains which often have longer return on investment (ROI) than market investments.

Limitations to the preciseness of the model are clearly evident throughout Chapter 2; as such the simulated cost values should not be used as an absolute measure of financial performance. The utility of the model, and life-cycle costing in general, is to identify budget allocation and timing. Without the model, stakeholders would not be able to observe what proportion of cost or benefit they have to carry or receive, pending other decisions outside of their control. In particular, operators are inevitably left carrying the burden of poor performance. At the end of Chapter 2, a flow chart describing decision flow shows how operational expertise can be integrated at the iteration point from each major design change. From an institutional point of view, this involvement can be achieved by direct participation by the future building operators in the IDP team. A life-cycle model can be used to guide budget efficiencies and track progress towards cost targets for both developer and operator. However, in a commercial market setting where new buildings are to be immediately sold, future operators are often not represented or completely unknown. In the latter case, there are possibilities for a strengthened commissioning process, where a third-party arms-length agent can represent the interests of future owners. Again, all decisions would be scrutinized by long-term costing and defensible under feasible future scenarios.

5.1.2 Objective 2

Attaining the second objective has many of the same challenges as the financial LCC analysis, but this time is founded on an environmental life-cycle:

> *"What are life-cycle environmental impacts for a building constructed to CIRS 'standard' compared to LEED Gold?"*

Chapter 3 examines the comparative impacts of the dynamic usage of CIRS relative to an equivalent of LEED Gold building. The goal of the analysis is to quantify the timing and extent of impacts as they occur, from a building-as-a-process point of view. Most previous life-cycle studies have omitted interior systems in the model and only focus on the structure. In contrast, the integrated LCA model, which includes selected interior systems, shows that overall embodied performance is a complex relationship between component prevalence, durability and churn rates. The integrated model reveals operational 'cross-over' points where short life-cycle components with fast, frequent, small impacts can rival or even exceed slow moving construction impacts. The faster moving systems are tied to occupancy type and behaviour, which means that evaluating environmental performance of a building requires careful consideration of changing occupancy levels when modeling. Future research would do well to focus on an occupant-centric model of life-cycle approaches, with an exploration of occupancy patterns at different scales, including individual, room and the building scales.

The findings show that strategies have different interpretations when viewed through an integrated model lens. For reducing construction impacts, the use of wood and fly ash are investigated in terms of effectiveness in reducing GWP impacts. The use of structural wood decreases the potential impact of CIRS by 64-134% (depending on the storage coefficients used) and the use of fly ash decreases impact by ~8%. In terms of a strategic capability to reduce life-cycle performance, both of these solutions are obtainable only once during building life. Failure to gain these benefits are permanently lost after construction, because later interventions are impractical and ineffective; the slow metabolism of structural systems adds only 12% recurring impacts over 50 years. In contrast, furnishings, fixtures and equipment have high metabolic rates and, in the case that technological evolution produces few operational improvements, could add recurring impacts of approximately 460% and 1000% for ICT and furniture, respectively (uncertainty is high). From a policy point of view, it is difficult to reduce embodied impacts without understanding the points of intervention. This finding of this study suggests that there are four main strategies available to decision-makers:

1. Reduce construction impacts at the outset of design because lock-in will last for decades, or possibly the entire life of the building
2. Identify the timing of replacements relative to their churn rates so that interventions can be planned in advance
3. Continuous optimization and LCA model updates so that any technological changes, or alternations to life span, can be planned in advance.

4. Plan for disposal and recycling. Understanding when devices are approaching end-of-life can enable pro-active waste management strategies

Sensitivity analysis shows that total aggregated impacts are highly sensitive to the life spans of each device, particularly devices such as LCD monitors that dominate the overall impact burden. Fortunately, the opportunities to reduce interior system impacts are numerous and available at every churn point. Note that because ICTs have very short innovation cycles, the models have high levels of uncertainty, meaning results obtained from simulations extending beyond10 years should be interpreted cautiously. Finally, LEED certification of buildings implies no consistent improvement over the UBC-LCA benchmark for embodied impacts. Similar inconsistency in operational performance data is discussed in Chapter 4.

Transportation impacts for structural systems are found to be small (<5% of total),, which brings into question the effectiveness of the localization policy encouraged by the Living Building Challenge. While there may be cultural or economic reasons for supporting local economies, environmental efficiencies are not observed in the results. With most impacts attributable to extraction and manufacturing, building rating systems such as LEED could demand clear evidence of improvements along the entire supply chain. This will be partly achieved with LEED's subtle shift in focus on rewarding products that have attained Environmental Product Declaration (EPD) standards, which by default require LCA during certification.

In terms of embodied versus operational impacts, the integrated model shows that for TRACI impact categories, CIRS achieves incremental gains over the LEED Gold base-case, with reductions across six of the seven TRACI metrics by a margin of 20-40%. The emphasis on storing wood to offset GWP has, depending on which storage co-efficient is used, enabled the structure to get close to, or do better than, net zero for COeq. In the case of using 1.6 t.CO2eq/m^3, CIRS' structure is regenerative (better than net zero). In contrast, using 0.76 t.CO2eq/m^3 means that the regenerative target is missed, although the building still performs better than the base-case. Further research is required to justify which coefficient is most appropriate.

Non-quantitative regenerative metrics are not possible to capture with the model. The scope of LCA and LCC is relatively confined and is unable to capture positive gains in social metrics such as well-being or workforce performance. Post occupancy evaluation can be used to track the performance of metrics for occupant comfort and satisfaction and, where possible, augmented with pre-occupancy evaluation so that the occupant expectation and background contextual issues can be evaluated.

5.1.3 Objective 3

Attaining the third objective required a focus on the community scale and a stronger emphasis on operational impacts.

> *"What are the community scale Carbon and Energy life-cycle impacts of LEED versus Conventional versus Regenerative for UBC core buildings?"*

The study utilizes metered EUI data on 80 buildings, all of which are co-located at UBC-V campus ,which eliminates regional and climate variability. The buildings also have comparable secondary energy sources, because almost all of the buildings are connected to a community energy system. The steam plant efficiency for the community thermal system is consistent across campus, meaning that the conversion of site energy to primary energy, right back to natural gas extraction, is virtually identical between buildings. This reduces model uncertainty.

For embodied impacts, the results find trends in GWP of UBC-V buildings related to construction year. Embodied impacts have risen steadily, primarily due to the increasing use of structural concrete technologies. If UBC hypothetically reconstructed the oldest buildings with current-day materials, the embodied effects average would be 0.16 $t.CO_{2eq}/m^2$ (1920-48 vintage). Buildings with the highest embodied GWP are from the 1960-2000 period, with an average intensity of 0.26 $t.CO_{2eq}/m^2$. For other TRACI environmental impact factors, recent buildings (especially laboratories) once again have higher embodied impacts than older structures. LEED certified buildings, although small in number in the dataset, show higher embodied impacts by 20-30%. However, the problem is not necessarily attributable to LEED, but more likely due to the widespread use of concrete. While the shift from wood to concrete buildings is certainly part of the reason for the lack of improvement in building performance over time, it cannot explain the continuing lack of improvement since concrete buildings have become prevalent. Other factors, such as the introduction of large atriums, the use of glass curtain walls, changes in seismic requirements, etc. are the likely culprits

The site operational energy performance of UBC-V, including thermal and electricity use, is found to be close to values found in the literature. For example, the median and mean of office buildings are 251 and 253 ekWh/m^2, respectively which is between 11-28% better than other well-known energy surveys (NRCAN, CIBEUS and CBECS). While this is encouraging, energy consumption is highly variable between buildings with no correlation with building age. Alarmingly, there is no significant energy performance advantage for buildings constructed in the early decades of UBC history, compared to recent structures. Similarly, there is no statistical improvement for LEED building performance over conventional buildings, though the number of buildings built to LEED building standards is still comparatively small. While there are no observable improvements when analyzing performance per floor area, increases in population density reveal clear community scale improvements when impact is normalized to per-capita metrics. Total core building steam consumption per person has declined by over 30% between 1994 to 2012. This density approach shows the importance of analyzing community scale dynamics in terms of densification and space utilization intensity, not just conventional EUI metrics.

Combining operational and construction impacts over a 50-year service life shows that conventional metrics, in particular primary energy and GWP, are mainly attributable to the operation phase and are in agreement with previous results in the LCA literature. Typically 85-95% of impacts occur during the operational phase during which they are dominated by energy consumption. However, the results are very different for other impact categories, for which embodied impacts can exceed operational impacts. For example, industrial particulate pollution and lake eutrophication embodied impacts are respectively 74% and 63% of total life-cycle 50-year[7] impacts. If stakeholders are only concerned with minimizing primary energy and GWP, then focusing on operational impacts is a sufficient strategy. If stakeholders choose to broaden the decision criteria, then evaluating construction phase impacts will become equally or more significant.

With regards to uncertainty, large variation in GWP impacts is linked to different choices for electrical generation emission factors. When the emission factor is input at 25 tCO_{2eq}/GWh, the total electrical GWP is not significant when compared to total thermal GWP (a ratio factor of approximately 1:9). When the electrical generation emission factor is increased to 140 tCO_{2eq}/GWh, then the ratio to thermal GWP declines to a ratio factor of only 1:2. This is because the emissions gap between electrical and thermal impacts becomes narrower as the EF factor for electricity rises. Emission factors are contested and if higher values are selected then electrical consumption should be minimized and any thermal provision directly via electricity should be avoided. Future research could look more deeply at the way emission factors are calculated, both in terms of time-of-day use (night imports have a higher emissions) and also the change in emission factors that will occur on the BC grid with regards to upcoming changes to generation demand and supply in Northern BC for LNG plants.

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[7] . Obviously, this proportion of embodied impacts will decrease as the building service life is increased because operational impacts aggregate rapidly.

Overall, the cause of operational variation between old and new buildings is of most concern. The lack of improvement by recent buildings cannot be pinpointed as a problem exclusive to LEED building approaches. Standards underpinning LEED, such as ASHRAE energy codes are not producing desired reductions. ASHRAE has increased the stringency of the 90.1 standard in almost every update since 1975; the aggregated incremental improvements should have yielded approximately 62% in energy savings. Despite improved energy regulation, stronger codes and more advanced building technologies, buildings are failing to produce consistent performance gains. This motivates further research to investigate other operational drivers associated with occupant use, such as plug loading and HVAC services.

5.2 Life-cycle approaches - model limitations and recommendations

There are several critical limitations to the integrated models that need to be addressed in future research as more high quality data becomes available. The recycling impacts are omitted from the analysis in Chapters 2, 3 and 4, and there are important questions that relate to end-of-life fate:

- The storage of CO2eq by wood is highly dependent on chain-of-custody for structural members when the building is deconstructed. Failure to re-use timbers, or permanently sequester the carbon, may mean an atmospheric return for embodied CO2.
- There are environmental gains that are missed by recycling components at end-of-life. The ongoing improvements in recycling rates mean that life-cycle system efficiency is increasing and the integrated models miss many of these benefits.

For example, the recovery and recycling rate of steel rebar has increased from 90-98% between 2001 and 2012, and similar recovery rates are evident for other metal components (Meijer & Europea 2002). Pinpointing the benefits of high levels of reuse and recycling are important for informing the decision to rebuild or replace which, in terms of sustainability, is a long standing debate (Thomsen & van der Flier 2009; Itard & Klunder 2007; Dong et al. 2005). If recycling and reuse offer low-impacts methods of replacing a building, then there is an argument for building deconstruction and replacement with more advanced structures[8].

- The technological trend of newer buildings is not resulting in efficiency improvements. A research imperative is to pinpoint the underlying reasons for the increase. As pointed out by Fedoruk (2013), advanced buildings have a number of additional challenges that prevent a realization of improvements. These include technologies that don't function as expected, are incorrectly monitored or have limited gains due to poor integration with existing systems. Conversely, many technologies may be successful but in ways that are difficult to directly measure. These include advanced window wall systems, large multi-floor atria, and seismic upgrades. Understanding these dimensions of multi-disciplinary performance, in terms of environmental and financial trade-offs, is outside the scope of the dissertation and will require further research work to determine

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- [8] However, the results of Chapter 4, where new buildings were found to offer no consistent improvement over their older counterparts, show that using tear-down and leveraging technological advancement to improve the overall building stock does not guarantee improvement. A future iteration of the models could include full recycling feedback loops to simulate material re-use and quantify different industrial ecology approaches of reuse and closed loop systems.

5.3 Benchmarking and suggestions for future use in design

Throughout the dissertation, case-study data is compared with either average or median benchmarking data (when available). There are future opportunities to use these benchmarks to inform design targets for whole-building performance

- The UBC-LCA database offers a possible solution for structural benchmarking and could help designers pick appropriate aspirational targets to work towards. In the context of an IPD (or IDP) structure, these targets can be developed as aspirational goals early in the design flow, and solidified into firm targets later in the decision-flow.
- Benchmarks can be developed for individual building systems, with ICT and furniture data from this study now available for use. With embodied impacts of devices found to scale linearly with their mass, rapid prototyping can be based on simple and informative heuristics at the design phase. With mass-impact relationships known for ICT, furniture and structural systems, targets can be set against the anticipated mass inputs of each system. These are reported at 31 kg CO2-eq per kg for ICT, 1.3 kg CO2-eq per kg for furnishings and ~0.2 kg CO2-eq per kg for structural impacts. While these benchmarks should not replace a full LCA, they provide a starting point for discussion.

5.4 Conclusion

The move towards sustainable buildings is accelerating and institutions, such as University of British Columbia (UBC), are formalizing approaches to structured decision-making for building systems. The integrated model results show a bewildering number of decision factors stemming from the complexity of environmental and financial performance dynamics. On the one hand decision makers need diverse information to represent the life-cycle impacts of each choice,; on the other, they need concise and streamlined data to expedite the decision process, often on tight deadlines. The rapid structuring, co-production and deliberation of environmental and financial data are essential for decision-makers, who often engage in numerous and concurrent small-scale decisions, tasks that dominate the building procurement cycle. During the integrated modeling process, stakeholder participation was secured to varying degrees for each sub-model. In many cases, experts from inside UBC contributed to the modeling process, including data input from suppliers such as Haworth, representing extensive collaboration in the project. The close participation of stakeholders and experts meant that their level of LCA literacy improved during the modeling process. This increased level of understanding meant that the final model results were simple to analyze, and rendered more meaningful for future use.

Most of the models used in this research were conducted *a posteriori* with regards to decision-making; however the UBC IT study was unique in that it was conducted specifically to assist the choice of ICT in CIRS. The expert input and co-generated data were engaged concurrently in decision-making, which had several interesting outcomes. Firstly, participants defined the project goal as a working group, which built-in a collective understanding of the model in terms of utility and limits. Secondly, the active participation of stakeholders enabled relatively straight-forward assimilation of complex data outputs, because the stakeholders were already familiar with the model structure.

Thirdly, model data gaps, a pervasive challenge to data completeness in life-cycle modeling, were bridged with expert 'tacit', or unrecorded, knowledge held by the stakeholders. Tacit knowledge was critical to building scenarios for the IT service mix, without which the model would have been greatly weakened. Further research could be conducted to quantify the utility and outcomes of this participatory approach. Stakeholder dynamics may be a key to understanding the way the team expedited model construction, perhaps due the small group size and interior cohesion coupled with low levels of internally competing priorities. Also of possible importance was the presence of a common goal and vision, coupled with institutional permission to take actions based on a broad set of metrics, not just financial cost minimization, that were likely strong factors leading to the successful use of life-cycle approaches. Future research could formally examine the effectiveness of participation, and find ways to generalize the process for use in IDP.

The research outcomes show the importance of considering the temporal context of replacement decisions. Planners also need to consider the best life-cycle intervention strategies to attain and maintain high financial and environmental performance. A good leverage point for reducing the impact of structural technologies is at the construction phase; such technologies are relatively easy to integrate and implement into technical requirements for an institution such as UBC. However, attaining continuous gains from fast moving interior systems is a moving target, and may be more challenging to codify and apply since these decisions fall into the domain of supply managers and operational staff. Further work will be required to identify the regulatory instruments required to assist, incentivize and enforce a high quality decision environment for building operation.

While the model results are useful for strategic planning, the model *process* is arguably more useful for generating coherence and capacity between stakeholders. This is in alignment with a procedural view of sustainability (Robinson 2004). The specific model results, and their use, lend themselves to instrumental sustainability, where the outcomes are used as levers to attain a specific end. The tension between the procedural versus instrumental dimensions of sustainability are prevalent throughout the dissertation and provides a useful lens for summarizing the key outcomes of the work. Life-cycle approaches are ostensibly about quantifying and simulating impacts over time, and the three manuscripts are all direct attempts at quantification with a view to providing useful information for performance comparisons against benchmarks. The dissertation has attempted to go one small step further, to find the relationships between systems using an integrative approach. Integrating models enables the observation of connections between decisions and stakeholders that appear, at first glance, to be disparate and unrelated. One of the strengths of an integrative life-cycle approach is the provision of a formal framework for identifying how new connections can be linked to informed decisions, which in turn can lead to improvements in environmental and financial efficiency. As an example, the integrative approach led to the discovery of contrasting metabolic rates of interior systems. The relative churn impacts reveal counter intuitive trends, all of which would not have been found without combined models built with the input from industrial partners, academic expertise and the collective input of students contributing to the UBC-LCA database.

With the main findings of the dissertation centered on life cycle approaches in terms of applied sustainability, future research could extend application in three dimensions; integration methods for scaling, utility for decision-making, and participation processes for modelling. Specifically, future work could investigate:

1. Building open access LCA models that have harmonized system boundaries and employ the same LCIA methods would enable rapid extensions of the integration approach. Currently, the ICT, FFE and construction sub-models comprise three core data sets. There are relatively few barriers to expanding sub-models to other building systems including, for example, geo-exchange and PV systems. With all models plugging into a central tool, a very comprehensive overview of an entire building system could emerge over successive studies. Plug-in modelling would represent an important innovation because most previous studies have been isolated one-off studies. The use of integration means that the results from different projects can each provide a piece of a jigsaw and assemble a broad picture of overall environmental performance.
2. Creating a fast-tracking approach to modelling could help provide more timely and relevant support for decision-makers. Currently, LCC and LCA are often too slow and cumbersome for planners. A rapid screening process could be formally developed using the order-of-magnitude estimation methods identified in Chapter 3. This would decrease the execution time and cost for modelling and enable a

tighter integration of scenario-based model results into the IDP. If required, more detailed modelling can be conducted on specific systems, as defined by IDP participants.

3. Developing more formal participation methods for the inclusion of stakeholder expertise during modelling. Formal methods should include clear technical guidelines on the appropriate acquisition and use of expert knowledge. In the case of institutional stakeholders, where participants are on payroll and have strict work priorities set out by their employment requirements, institutions should grant permission for employees to participate as part of their professional practice. On the other hand, institutions need very clear assurance that participation is an efficient use of workforce time and that deliverables from a participatory model creates value, both in terms of high-quality decision-making and sustainability reporting.

This type of collaboration points the way to future work with life-cycle approaches that, in a participatory environment, can be used as a sustainability ‘lens’ to reveal how stakeholders are connected and how they can collectively mitigate risk, identify co-benefits and develop benchmarks for tracking progress.

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Appendices

Appendix A Benchmarking for LCA

A.1 Life-cycle approaches for benchmarking and standardization

Measuring and benchmarking for energy consumption at the building scale is sporadically moving forward. Simultaneous with recent efforts for standardization of reporting, benchmarking is being used for targeting levels of acceptable carbon emissions and energy use. However, there is a current lack of clarity concerning the meaning of targets like carbon 'neutral' (Zuo et al. 2012). At a high level, the European Union (EU) has responded with directives on energy performance reporting and labeling (EU n.d.). EU Member States have tasked governmental organizations such as the UK Department of Energy and Climate Change (DECC) to push for greater clarity with regards to transparency and definitions for carbon neutrality. The UK DECC, and others, have selected the PAS2050 carbon accounting methodology as being a high quality standard (DECC 2009; British Standards Institute 2011).

In contrast, benchmarking in North America emerges from smaller scales and percolates upwards. Numerous initiatives are now underway including the Carbon Neutral Design Project by the Society of Building Science Educators (SBSE) and American Institute of Architects (AIA) as a means to meet the 2030 Challenge. Additionally, the National Renewable Energy Laboratory (NREL), the National Institute of Standards and Technology (NIST) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Vision 2020 have weighed in for guidance with net zero-energy buildings (Crawley et al. 2009; Townsend 2008; Pellegrino et al. 2010). Benchmarking for existing buildings has become more widespread since the 2003 and 2007 voluntary Commercial Buildings Energy Consumption Surveys (CBECS) surveys; municipal by-laws have enforced annual energy and water benchmark reporting for city buildings in at least five US cities including New York, San Francisco, Austin, Seattle and Washington, D.C.

Life-cycle approaches are widely regarded as a useful launching point for benchmarking the impacts of products and processes and for formalizing GHG accounting (WRI 2011; SCS 2009). While benchmarking has been making progress from a consumption (operational) viewpoint, confusion remains about how to evaluate life-cycle impacts. Current tools used for environmental assessment have been dominated by rating systems such as LEED, GreenGlobes and BREEAM. From a life-cycle point of view, the assessment methods have various levels of inclusion but no standard homogenous method of reporting. Ng (2013) compares and contrasts approaches for carbon emissions reporting within BREEAM, BEAM Plus, LEED, CASBEE, Green Mark and Green Star and finds large variation between both methods and results (Ng et al. 2013). Ng suggests that moving forward towards establishing reproducible methods needs a collective, sector-wide effort to agree on standardized approaches. The AIA point out that benchmarking remains the last unresolved issue for LCA and requires national scale agencies and organizations, such as Environmental Protection Agency (EPA), to establish industry averages for building scale LCA studies. Similarly for LCC, the tool is often regarded highly as a sustainability financial assessment tool, but methods and benchmarking are underused for measuring sustainability. Chapters 2, 3, and 4 discuss and report on local and regional benchmarks with a focus on UBC specific surveys.

The benchmarks are used to compare and contrast CIRS and LEED Gold for relative performance. The methodology is exportable for larger scale initiatives in the future.

Model Implementation:

The model was built in Excel with separate modules to calculate LEED costs using the UBC Infrastructure Development model. Separate worksheets detailing Corix costs were integrated into the Excel model, which included specialized costs for the geothermal heating and cooling system, the solar hot water system, and the rainwater collection system. A functional programming statement from Perkins and Will was also included with a separate harmonizing calculation sheet required to map architectural programming categories into operational ID categories. The ID model, which was a large spreadsheet, was later physically integrated into the model once a more computationally powerful computer was acquired. The ID model handled non-specialized costs from Whitestone data. On the front end of the Excel model, a full scenario engine was developed for computing the cost of various energy futures. A Monte Carlo tool was developed in an entirely separate worksheet due to the large data requirements.

A.2 First cost data supplemental

Table A-1 First cost regression curve with standard deviation bands.

Building Area	Regression Curve
10000	$3,839,491
20000	$7,266,271
30000	$10,552,817
40000	$13,751,482
50000	$16,886,350
60000	$19,971,298
70000	$23,015,342
80000	$26,024,801
90000	$29,004,346
100000	$31,957,566
110000	$34,887,302
120000	$37,795,857
130000	$40,685,136
140000	$43,556,736
150000	$46,412,022
160000	$49,252,164
170000	$52,078,185
180000	$54,890,980
190000	$57,691,342
200000	$60,479,975
210000	$63,257,514
220000	$66,024,526
230000	$68,781,529
240000	$71,528,992
250000	$74,267,344

Source: Storey (2012)

Table A-2 Escalated costs used in construction cost chart.

	GSF Area (BOG reports) Units ft^2	Escalated Board 3 or 4 Total Construction Costs
Comparable UBC Buildings (2000-2012)	18,836	$6,809,728
	156,325	$47,505,577
	123000	$37,127,819
	122,546	$40,675,822
	239,873	$60,107,001
	80923	$35,617,752
	85000	$26,822,228
	20,324	$8,143,628
	97154	$25,229,234
	52,770	$13,478,420
	164020	$71,665,260
CIRS	60816	$28,094,035

Source: UBC Board of Governors Records. Accessed Oct, 2011. Stats Canada Construction price index for escalation rates..

A.3 Data for total cost of ownership simulation.

Table A-3 Board of governors public cost data showing cost items included in LCC

		Curtis Law (Board 3, Jun 30th 2009)	Liu (Board 4, Nov 2002)	ISICS/CS (Board 4, May 2006)	W&W White (Board 3, Feb 2010)	Kaiser (Board 3, Sept 2007)	AERL (Board 4 Nov 2006)	ESB (Board 3 June 2010)	Chem Bio (June 2004)	Beaty Bio (June 2006)	I.K. Barber (Feb 2008)	Michael Smith (May 2006)
	Building Area	**$1.4E+05**	**$1.9E+04**	**$8.1E+04**	**$2.0E+04**	**$9.7E+04**	**$5.3E+04**	**$1.6E+05**	**$1.2E+05**	**$1.2E+05**	**$2.4E+05**	**$8.5E+04**
	General Requirements					$1.0E+06	$6.1E+05		$1.4E+06	$2.6E+05	$6.0E+06	$1.0E+06
	Construction Fee					$3.1E+05			$5.1E+05	$1.1E+06	$1.1E+06	$3.4E+05
(Total Hard Construction Cost)	**Subtotal: Building Components**	**$3.7E+07**	**$3.6E+06**	**$2.0E+07**	**$6.2E+06**	**$1.6E+07**	**$8.0E+06**	**$5.5E+07**	**$2.7E+07**	**$3.5E+07**	**$5.6E+07**	**$1.8E+07**
General Soft Costs	Allowances (Contingency)	$1.8E+06		$1.9E+06	$3.0E+05	$6.5E+05	$4.0E+05	$2.1E+06	$1.9E+06	$1.9E+06	$1.1E+04	$1.1E+06
	Consultant Fees	$4.3E+06		$3.8E+06	$9.4E+05	$2.2E+06	$1.1E+06	$6.8E+06	$2.6E+06	$3.9E+06	$7.6E+06	$3.0E+06
	Permits and Fees	$7.5E+05		$3.5E+05	$1.6E+05	$2.4E+05	$0.0E+00	$6.0E+05		$4.4E+05	$2.5E+05	
	Project Management	$1.4E+06		$7.8E+05	$3.0E+05	$5.0E+05	$2.5E+05	$1.6E+06	$6.0E+05	$8.0E+05	$9.0E+05	$4.5E+05
	Fee						$1.3E+05					
	PV					$1.0E+05	$0.0E+00					
	Inspection and Testing Fees			$3.5E+05			$1.3E+05		$1.5E+05		$9.5E+04	$2.7E+05
	Commissioning	$1.0E+05	$7.8E+05	$1.5E+05	$0.0E+00	$7.5E+04	$7.5E+04		$7.5E+04	$2.0E+05	$2.7E+04	$7.5E+04
	Subtotal: Building Components + Soft Costs	**$4.5E+07**	**$4.4E+06**	**$2.7E+07**	**$7.9E+06**	**$2.0E+07**	**$1.0E+07**	**$6.6E+07**	**$3.3E+07**	**$4.2E+07**	**$6.5E+07**	**$2.3E+07**
	GST @ 1.66%	$7.5E+05	$7.3E+04	$4.5E+05	$1.3E+05	$3.4E+05	$1.7E+05	$1.1E+06	$5.4E+05	$7.0E+05	$1.1E+06	$3.8E+05
	Total Building Costs	$4.6E+07	$4.5E+06	$2.7E+07	$8.0E+06	$2.1E+07	$1.0E+07	$6.7E+07	$3.3E+07	$4.3E+07	$6.6E+07	$2.3E+07
UBC Specific Soft Costs	FFE			$1.1E+06	$1.8E+05	$6.5E+05	$4.1E+05	$2.7E+06	$5.0E+05	$5.0E+05	$3.5E+06	$6.4E+05
	UBC IT/AV Allowance	$2.4E+06	$5.3E+05	$9.5E+05	$2.5E+05	$5.0E+05	$2.3E+06	$8.5E+05	$3.5E+05	$2.3E+05	$1.4E+05	$5.3E+05
	Sub-Total	**$2.4E+06**	**$5.3E+05**	**$2.0E+06**	**$4.3E+05**	**$1.1E+06**	**$2.7E+06**	**$3.6E+06**	**$8.5E+05**	**$7.2E+05**	**$3.7E+06**	**$1.2E+06**
	GST (1.67%)	$3.9E+04	$8.8E+03	$3.4E+04	$7.2E+03	$1.9E+04	$4.5E+04	$6.0E+04	$1.4E+04	$1.2E+04	$6.1E+04	$1.9E+04

		Curtis Law	Liu	ISICS/CS	W&W White	Kaiser	AERL	ESB	Chem Bio	Beaty Bio	I.K. Barber	Michael Smith
Specialist Costs (removed from LCC to enable comparability between projects)	Site and Relocation Costs											
	Offsites	$9.0E+05		$5.6E+05		$3.3E+05	$2.2E+05		$8.0E+04		$1.2E+06	$4.4E+05
	Onsites			$7.2E+05		$1.4E+06	$1.8E+05		$2.5E+05		$4.6E+05	$5.0E+05
	Construction carrying costs											
	Demolition	$8.0E+05						$5.0E+05			$3.1E+06	
	Temporary Facilities	$1.8E+06						$8.0E+05				
	Moving Allowance			$3.5E+05		$2.0E+05	$1.3E+05		$7.5E+04	$2.5E+05	$6.3E+05	$1.4E+05
	Lab equip, software, workstations			$8.5E+06			$2.0E+06		$4.0E+06	$4.7E+06	$3.6E+06	$4.4E+06
	Fire/Safety, Seismic Upgrades			$4.5E+05		$2.6E+06				$2.0E+05		
	Library furnishings	$1.6E+06										
	GST (1.67%)	$9.0E+04				$8.0E+04	$4.5E+04	$2.3E+04	$7.8E+04	$9.1E+04	$1.6E+05	$9.6E+04
	Retained Risk	$5.3E+05										
	Financing	$1.7E+06										
	P3 Indicative Design Sunk Costs and Projected Interest Charges							$2.0E+06				
	Sub-Total	$7.4E+06	$0.0E+00	$1.1E+07	$0.0E+00	$4.6E+06	$2.6E+06	$3.3E+06	$4.5E+06	$5.3E+06	$9.1E+06	$5.6E+06
	Status in LCC comparison	(not carried)	(not carried)	(not carried)	(not carried)	(not carried)	(not carried)	(not carried)	(not carried)	(not carried)	(not carried)	(not carried)
Total unescalated costs												
	Total Estimated Cost (used for LCC comparison)	$5.6E+07	$5.0E+06	$4.0E+07	$8.4E+06	$2.6E+07	$1.6E+07	$7.4E+07	$3.8E+07	$4.9E+07	$7.9E+07	$3.0E+07
	Total Estimated Cost for LCC	**$4.8E+07**	**$5.0E+06**	**$2.9E+07**	**$8.4E+06**	**$2.2E+07**	**$1.3E+07**	**$7.1E+07**	**$3.4E+07**	**$4.4E+07**	**$7.0E+07**	**$2.4E+07**

Source: UBC Board of Governors Records. Accessed Oct, 2011.

Table A-4 Simulated total cost of ownership data for 50 year service life.

Accumulated total cost of ownership (Building, discount rate)										
Year	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Market Accumulated Total (CIRS, 5%)	0.0E+00	2.9E+07	3.0E+07	3.1E+07	3.2E+07	3.2E+07	3.3E+07	3.4E+07	3.4E+07	3.5E+07
Social Accumulated Total (CIRS, 3%)	0.0E+00	2.9E+07	3.0E+07	3.1E+07	3.2E+07	3.3E+07	3.3E+07	3.4E+07	3.5E+07	3.5E+07
Social Accumulated Total (Base case, 3%)	0.0E+00	2.2E+07	2.3E+07	2.4E+07	2.6E+07	2.7E+07	2.8E+07	2.8E+07	3.0E+07	3.0E+07
Market Accumulated Total (Base case, 5%)	0.0E+00	2.2E+07	2.3E+07	2.4E+07	2.5E+07	2.6E+07	2.7E+07	2.8E+07	2.9E+07	3.0E+07
Year	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Market Accumulated Total (CIRS, 5%)	3.5E+07	3.6E+07	3.6E+07	3.7E+07	3.7E+07	3.8E+07	3.8E+07	3.8E+07	3.9E+07	3.9E+07
Social Accumulated Total (CIRS, 3%)	3.6E+07	3.7E+07	3.7E+07	3.8E+07	3.8E+07	3.9E+07	4.0E+07	4.0E+07	4.1E+07	4.1E+07
Social Accumulated Total (Base case, 3%)	3.2E+07	3.3E+07	3.3E+07	3.4E+07	3.5E+07	3.6E+07	3.7E+07	3.8E+07	3.8E+07	3.9E+07
Market Accumulated Total (Base case, 5%)	3.1E+07	3.1E+07	3.2E+07	3.2E+07	3.3E+07	3.4E+07	3.5E+07	3.5E+07	3.5E+07	3.6E+07
Year	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Market Accumulated Total (CIRS, 5%)	4.0E+07	4.0E+07	4.0E+07	4.0E+07	4.1E+07	4.1E+07	4.1E+07	4.1E+07	4.2E+07	4.2E+07
Social Accumulated Total (CIRS, 3%)	4.2E+07	4.2E+07	4.3E+07	4.3E+07	4.4E+07	4.4E+07	4.5E+07	4.5E+07	4.6E+07	4.6E+07
Social Accumulated Total (Base case, 3%)	4.2E+07	4.2E+07	4.3E+07	4.3E+07	4.4E+07	4.5E+07	4.5E+07	4.6E+07	4.6E+07	4.7E+07
Market Accumulated Total (Base case, 5%)	3.8E+07	3.8E+07	3.8E+07	3.9E+07	3.9E+07	4.0E+07	4.0E+07	4.0E+07	4.0E+07	4.1E+07
Year	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**
Market Accumulated Total (CIRS, 5%)	4.2E+07	4.2E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.4E+07	4.4E+07
Social Accumulated Total (CIRS, 3%)	4.6E+07	4.7E+07	4.7E+07	4.8E+07	4.8E+07	4.8E+07	4.9E+07	4.9E+07	4.9E+07	5.0E+07
Social Accumulated Total (Base case, 3%)	4.8E+07	4.9E+07	4.9E+07	5.0E+07	5.0E+07	5.0E+07	5.1E+07	5.1E+07	5.2E+07	5.2E+07
Market Accumulated Total (Base case, 5%)	4.2E+07	4.2E+07	4.2E+07	4.2E+07	4.2E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07	4.3E+07
Year	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**
Market Accumulated Total (CIRS, 5%)	4.4E+07	4.4E+07	4.4E+07	4.4E+07	4.4E+07	4.4E+07	4.5E+07	4.5E+07	4.5E+07	4.5E+07
Social Accumulated Total (CIRS, 3%)	5.0E+07	5.0E+07	5.1E+07	5.1E+07	5.1E+07	5.1E+07	5.2E+07	5.2E+07	5.2E+07	5.2E+07
Social Accumulated Total (Base case, 3%)	5.4E+07	5.4E+07	5.4E+07	5.4E+07	5.5E+07	5.5E+07	5.6E+07	5.6E+07	5.6E+07	5.6E+07
Market Accumulated Total (Base case, 5%)	4.4E+07	4.4E+07	4.4E+07	4.4E+07	4.4E+07	4.5E+07	4.5E+07	4.5E+07	4.5E+07	4.5E+07

Source: Storey (2012).

Appendix B Integrated model LCA data

B.1 ICT data summary

Per-device data is sourced from (Teehan & Storey 2012). The work relied on the ecoinvent LCI data, which included full LCA models of a desktop, laptop, LCD monitor and network modem (Teehan & Storey et al. 2011). Those models were adapted to create surrogate inventories of modern products based on assumptions of composition of those products, in terms of key modules like casing, circuit boards and displays. The masses of modern products were estimated based on information on manufacturer's websites; masses and dimensions of key modules were estimated based on total product mass, overall dimensions, and the characteristics of products already modeled in ecoinvent. A later study by Teehan et al. (Teehan & Kandlikar 2013), using a full process LCA, showed impacts to be generally smaller than early ecoinvent database due to technological advances which enable more materially efficient designs, and especially higher levels of integration resulting in fewer boards and chips.

Table B-1 ICT Per device data.

	Blade	Desktop	Desktop-lite	LCD	Keyboard	Mouse	Laptop	Thin client	POE phone	usb phone	Eth switch	WAP	Headset	Cat5
Production LCIA per device (TRACI impact scheme)														
Global warming	5.5E+02	2.7E+02	1.0E+02	3.3E+02	2.6E+01	5.1E+00	2.1E+02	4.5E+01	3.2E+01	1.6E+01	3.0E+02	1.6E+01	2.4E+00	4.3E-01
Acidification	1.9E+02	9.4E+01	3.7E+01	1.2E+02	8.4E+00	1.8E+00	5.4E+01	1.6E+01	1.1E+01	5.4E+00	1.1E+02	4.6E+00	6.9E-01	2.7E-01
Carcinogenics	2.4E+01	1.0E+01	4.2E+00	5.8E+00	9.5E-01	2.1E-01	5.3E+00	1.7E+00	1.1E+00	7.0E-01	1.2E+01	4.9E-01	8.9E-02	5.2E-02
Non carcinogenics	3.1E+05	1.4E+05	4.4E+04	6.4E+04	1.3E+04	2.4E+03	6.6E+04	1.9E+04	6.8E+03	3.7E+03	1.3E+05	2.7E+03	4.8E+02	2.8E+02
Respiratory effects	9.9E-01	5.3E-01	2.0E-01	5.5E-01	4.6E-02	9.6E-03	2.9E-01	8.6E-02	5.7E-02	3.0E-02	6.1E-01	2.6E-02	3.7E-03	1.5E-03
Eutrophic.	1.5E+01	5.8E+00	2.3E+00	4.9E+00	4.9E-01	1.1E-01	3.4E+00	1.1E+00	4.1E-01	2.0E-01	6.9E+00	1.8E-01	2.1E-02	1.1E-02
Ozone depletion	5.8E-05	2.7E-05	9.2E-06	2.0E-05	2.5E-06	4.8E-07	1.5E-05	4.2E-06	2.6E-06	1.2E-06	2.9E-05	1.4E-06	7.7E-08	4.0E-08
Ecotoxicity	1.5E+04	6.3E+03	2.3E+03	3.5E+03	6.4E+02	1.2E+02	3.5E+03	1.0E+03	3.4E+02	1.8E+02	6.7E+03	1.5E+02	2.2E+01	1.2E+01
Smog	1.7E+00	7.6E-01	2.8E-01	8.8E-01	6.6E-02	1.3E-02	4.2E-01	1.2E-01	7.6E-02	3.8E-02	8.5E-01	3.3E-02	5.1E-03	1.5E-03
Device lifetime	4.0E+00	4.0E+00	4.0E+00	6.0E+00	6.0E+00	6.0E+00	3.0E+00	8.0E+00	8.0E+00	8.0E+00	6.0E+00	6.0E+00	3.0E+00	4.0E+01

Source: Teehan (2012).

Per building data is based on a ICT survey of AERL and, later, expert input from UBC IT for the requirements of the CIRS building inhabitants. The device scale data is shown normalized to the lifespan of each device and then reported as per year impacts. Note that the current 2014 inventory of devices will differ from these early 2012 estimate. Source: (Teehan & Storey 2012).

Table B-2 ICT Per building ICT data.

	Blade	Desktop	Desktop-lite	LCD	Keyboard	Mouse	Laptop	Thin client	POE phone	usb phone	Eth switch	WAP	H-set	Cat5
CIRS Devices	3	40	20	200	200	200	40	100	100	0	8	33	0	32000
Production LCIA / yr														
CIRS - GWP	4.13E+02	2.69E+03	5.00E+02	1.11E+04	8.57E+02	1.68E+02	2.77E+03	5.57E+02	4.04E+02	-	4.06E+02	8.59E+01	-	3.43E+02
Acidification	1.40E+02	9.35E+02	1.86E+02	4.03E+03	2.81E+02	6.07E+01	7.23E+02	2.02E+02	1.34E+02	-	1.49E+02	2.51E+01	-	2.19E+02
Carcinogenics	1.82E+01	9.96E+01	2.12E+01	1.94E+02	3.17E+01	7.00E+00	7.05E+01	2.14E+01	1.41E+01	-	1.55E+01	2.68E+00	-	4.16E+01
Non carcinogenics	2.34E+05	1.39E+06	2.19E+05	2.12E+06	4.20E+05	8.13E+04	8.73E+05	2.37E+05	8.46E+04	-	1.67E+05	1.51E+04	-	2.28E+05
Respiratory effects	7.45E-01	5.25E+00	1.02E+00	1.85E+01	1.54E+00	3.20E-01	3.83E+00	1.08E+00	7.16E-01	-	8.09E-01	1.44E-01	-	1.21E+00
Eutrophic.	1.12E+01	5.80E+01	1.16E+01	1.62E+02	1.64E+01	3.77E+00	4.51E+01	1.32E+01	5.16E+00	-	9.25E+00	9.63E-01	-	8.47E+00
Ozone depletion	4.37E-05	2.66E-04	4.62E-05	6.67E-04	8.40E-05	1.61E-05	1.96E-04	5.29E-05	3.20E-05	-	3.81E-05	7.59E-06	-	3.22E-05
Ecotoxicity	1.14E+04	6.25E+04	1.15E+04	1.17E+05	2.12E+04	4.13E+03	4.72E+04	1.27E+04	4.30E+03	-	8.88E+03	8.00E+02	-	9.64E+03
Smog	1.26E+00	7.64E+00	1.41E+00	2.92E+01	2.20E+00	4.47E-01	5.55E+00	1.54E+00	9.46E-01	-	1.14E+00	1.80E-01	-	1.23E+00
AERL - Device	3	80	0	200	200	200	100	20	100	0	8	33	0	32000
Production LCIA / yr														
AERL - GWP	4.13E+02	5.38E+03	-	1.11E+04	8.57E+02	1.68E+02	6.93E+03	1.11E+02	4.04E+02	-	4.06E+02	8.59E+01	-	3.43E+02
Acidification	1.40E+02	1.87E+03	-	4.03E+03	2.81E+02	6.07E+01	1.81E+03	4.03E+01	1.34E+02	-	1.49E+02	2.51E+01	-	2.19E+02
Carcinogenics	1.82E+01	1.99E+02	-	1.94E+02	3.17E+01	7.00E+00	1.76E+02	4.28E+00	1.41E+01	-	1.55E+01	2.68E+00	-	4.16E+01
Non carcinogenics	2.34E+05	2.78E+06	-	2.12E+06	4.20E+05	8.13E+04	2.18E+06	4.75E+04	8.46E+04	-	1.67E+05	1.51E+04	-	2.28E+05
Respiratory effects	7.45E-01	1.05E+01	-	1.85E+01	1.54E+00	3.20E-01	9.57E+00	2.16E-01	7.16E-01	-	8.09E-01	1.44E-01	-	1.21E+00
Eutrophic.	1.12E+01	1.16E+02	-	1.62E+02	1.64E+01	3.77E+00	1.13E+02	2.64E+00	5.16E+00	-	9.25E+00	9.63E-01	-	8.47E+00
Ozone depletion	4.37E-05	5.32E-04	-	6.67E-04	8.40E-05	1.61E-05	4.90E-04	1.06E-05	3.20E-05	-	3.81E-05	7.59E-06	-	3.22E-05
Ecotoxicity	1.14E+04	1.25E+05	-	1.17E+05	2.12E+04	4.13E+03	1.18E+05	2.54E+03	4.30E+03	-	8.88E+03	8.00E+02	-	9.64E+03
Smog	1.26E+00	1.53E+01	-	2.92E+01	2.20E+00	4.47E-01	1.39E+01	3.08E-01	9.46E-01	-	1.14E+00	1.80E-01	-	1.23E+00

B.2 Component life span

Life span data is sourced from (Teehan & Storey 2012), (Haworth, 2009-2012), (Bowick 2013). The data for Haworth systems is proprietary and is aggregated for discretion. The whisker plot analytics were completed using the R statistical program.

Table B-3 Statistical data for component life span.

	Information & Computing	Furniture Systems	Building Structure
Count	12.0	9.0	6.0
Mean	8.3	13.6	50.8
SD	10.1	5.2	35.6
Min	3.0	8.0	5.0
Q1	4.0	10.0	25.0
Median	6.0	12.0	55.0
Q3	6.5	15.0	70.0
Max	40.0	25.0	100.0
Bottom	4.0	10.0	25.0
2Q Box	2.0	2.0	30.0
3Q Box	0.5	3.0	15.0
Whisker-	1.0	2.0	20.0
Whisker+	33.5	10.0	30.0
Offset	0.5	1.5	2.5

Source: (Teehan & Storey 2012), (Haworth, 2009-2012), (Bowick 2013).

B.3 Life-phase specific data for AERL and CIRS

The life-phase LCIA data was completed from two individual LCA studies. The AERL study was conducted personally by Rob Sianchuk, the CIRS study by a CVL 498C team, which included input by Sianchuk. The CIRS model required many specific workarounds due to the novel systems in the building. Several key components have been omitted due to the lack of verifiable data. This includes the soil on the green roof, the PV system, geoexhange system and EOS heat exchange. These will require separate studies for completion. The Athena EIE bill of materials (BoM) had an additional check by the author. An alternate bill of materials was generated by extracting materials via the CIRS Revit structural CAD model. Further assistance was obtained from Max Richter at Perkins and Will architects on this method. The material BoM Revit analysis focused on wood and concrete elements only (these deemed most important for the CIRS design team).

Table B-4 Life phase data for selected TRACI impact categories.

AERL Normalized to UBC av.					
	Manufacturing		Construction		
	Manufacturing Material	Manufacturing Transportation	Construction Material	Construction Transportation	Total Initial
Prim. Ener.	1.0176	0.0194	0.0192	0.0511	1.1074
GWP	0.9989	0.0004	0.0154	0.0010	1.0158
Acidification	1.0138	0.0003	0.0180	0.0008	1.0329
HH Resp.	1.1947	0.00005	0.0025	0.0001	1.1973
Eutrophic.	0.7726	0.0003	0.0178	0.0008	0.7916
Smog Pot.	0.8523	0.0006	0.0375	0.0015	0.8920
CIRS Normalized to UBC av.					
	Manufacturing		Construction		
	Manufacturing Material	Manufacturing Transportation	Construction Material	Construction Transportation	Total
Prim. Ener.	0.5510	0.0193	0.0194	0.0290	0.6188
GWP	0.6166	0.0004	0.0158	0.0006	0.6334
Acidification	0.7137	0.0003	0.0193	0.0005	0.7337
HH Resp.	0.9782	0.00005	0.0027	0.0001	0.9810
Eutrophic.	0.5351	0.0003	0.0194	0.0005	0.5553
Smog Pot.	0.6669	0.0006	0.0401	0.0009	0.7085

Source: Sianchuk and Storey (2012).

Table B-5 Material Summary Data.

	UBC Average	**CIRS**	**AERL**
	(kg/m2)	(kg/m2)	(kg/m2)
Wood	7.2	88.4	0.1
Wall Coverings	22.8	15.0	32.9
Metal	43.9	22.5	51.6
Roof Materials	14.5	15.9	1.4
Masonry/Bricks	96.7	44.6	35.4
Concrete	1232.7	696.3	1109.9
Insulation	3.6	3.5	6.7
Glass	2.0	14.5	0.8
Plastics	0.1	0.1	0.2
Miscellaneous	0.038	0.009	0.005

Source: Sianchuk and Storey (2012).

B.4 UBC-LCA data-base overview

The UBC-LCA data-base is generated by the work of four years worth of senior undergraduate team projects. The course is managed by Robert Sianchuk and instructor for CIVL 498C) who has conducted reviews of each LCA project report. It is important to contextualize that, while the database represents the single largest body of building LCA work in North America, the reports are generated by students and are therefore of variable quality. The student final reports have been reviewed but, due to time and resource constraints, not all individual Athena EIE models have been inspected in significant detail. The database is comprised of 29 Academic buildings and 6 Residences that have reports completed by over 100 CIVL 498C students. All reports have an initial review for grading, and later subsequent reviews where inputs were adjusted to increase their consistency with the study Goal and Scope and representation of actual building attributes. The remainder of this appendix has been authored by Rob Sianchuk, for guidance on use and limitations on the database content and is published here with his permission. The database has been developed without a budget and represents a tremendous service effort by Sianchuk and his students to further research efforts on building LCA. Additional help was secured from UBC Infrastructure Development which generously supplied many of the extensive architectural records free of charge.

The current state of review, as of December 2013, is shown in Table B.6.

Table B-6 Review status for each UBC-LCA database building.

Building Type	Building Name	Building Number	Study Review State
Academic			
	AERL	316	secondary review
	Angus	023	secondary review
	Buchanan All	121 - all	secondary review
	CEME	306	secondary review
	Chem Physics	447	secondary review
	ChemBio	300	initial review
	Chemistry	132	secondary review
	Chemistry - North	136	secondary review
	Chemistry - South	148	initial review
	Curtis	480	initial review
	Curtis Addition	481	secondary review
	EOS - East	406	initial review
	EOS - Main	402	secondary review
	EOS - South	403	initial review
	FNH	449	initial review
	FSC	353	secondary review
	Geography	401	secondary review
	Hebb	656	secondary review
	Henn	652	secondary review
	ICICS/CS	165	initial review
	Kaiser	313	secondary review
	Kenny	732	secondary review
	Klink	308	secondary review
	Lasserre	028	secondary review
	MacMillan	386	secondary review
	Math	518	initial review
	Music	575	initial review
	Scarfe	232	secondary review
	Wesbrook	864	initial review
Residence			
	Fairview	007	secondary review
	Totem	540, 565	secondary review
	Vanier	545, 548, 552, 556, 560, 896	secondary review
	Marine Drive	377-3	secondary review
	Gage	869	secondary review
	Thunderbird	782, 783, 784	secondary review

Source: Sianchuk (2011).

Goal and Scope Template

As part of the course work, all student teams had strict guidelines for conducting each LCA. This involved using a template for defining the goal and scope for their models based on ISO 14040 protocols. Additionally, methods were developed for the use of OnScreen TakeOff version 3.6.2.25, a tool specifically designed for examining and extracting quantity survey data from architectural drawings. All models are built using an identical methodology and

LCIA calculations are based on the EPA TRACI lifecycle impact assessment method for quantifying environmental impacts. The template for conducing an LCA for the UBC-LCA database is shown below:

Goal of Study

This life-cycle analysis (LCA) of the [*insert Building Name*] building at the University of British Columbia was carried out as an exploratory study to determine the environmental impact of its design. This LCA of the [*insert Building Name*] building is also part of a series of twelve others being carried out simultaneously on respective buildings at UBC with the same goal and scope.

The main outcomes of this LCA study are the establishment of a materials inventory and environmental impact references for the [*insert Building Name*] building. An sample application of these references is in the assessment of potential future performance upgrades to the structure and envelope of the [*insert Building Name*] building. When this study is considered in conjunction with the twelve other UBC building LCA studies, further applications include the possibility of carrying out environmental performance comparisons across UBC buildings over time and between different materials, structural types and building functions. Furthermore, as demonstrated through these potential applications, this [*insert Building Name*] building LCA can be seen as an essential part of the formation of a powerful tool to help inform the decision-making process of policy makers in establishing quantified sustainable development guidelines for future UBC construction, renovation and demolition projects.

The intended core audiences of this LCA study are those involved in building development related policy making at UBC, such as the Sustainability Office, who are involved in creating policies and frameworks for sustainable development on campus. Other potential audiences include developers, architects, engineers and building owners involved in design planning, as well as external organizations such as governments, private industry and other universities that may want to learn more or become engaged in performing similar LCA studies within their organizations.

Scope of Study

The product system being studied in this LCA is the structure, envelope and operational energy usage associated with space conditioning of the [*insert Building Name*] building on a square foot finished floor area of Academic building basis. In order to focus on design related impacts, this LCA encompasses a cradle-to-gate scope that includes the raw material extraction, manufacturing of construction materials, and construction of the structure and envelope of the [*insert Building Name*] building, as well as associated transportation effects throughout.

Tools, Methodology and Data

Two main software tools are to be utilized to complete this LCA study; OnCenter's OnScreen TakeOff and the Athena Sustainable Materials Institute's Impact Estimator (IE) for buildings.

The study will first undertake the initial stage of a materials quantity takeoff, which involves performing linear, area and count measurements of the building's structure and envelope. To accomplish this, OnScreen TakeOff version 3.6.2.25 is used, which is a software tool designed to perform material takeoffs with increased accuracy and speed in order to enhance the bidding capacity of its users. Using imported digital plans, the program simplifies the calculation and measurement of the takeoff process, while reducing the error associated with these two activities. The measurements generated are formatted into the inputs required for the IE building LCA software to complete the takeoff process. These formatted inputs as well as their associated assumptions can be viewed in Annexes A and B respectively.

Using the formatted takeoff data, version 4.0.51 of the IE software, the only available software capable of meeting the requirements of this study, is used to generate a whole building LCA model for the [*insert Building Name*] building in the Vancouver region as an Institutional building type. The IE software is designed to aid the building community in making more environmentally conscious material and design choices. The tool achieves this by applying a set of algorithms to the inputted takeoff data in order to complete the takeoff process and generate a bill of materials (BoM). This BoM then utilizes the Athena Life-cycle Inventory (LCI) Database, version 4.6, in order to generate a cradle-to-grave LCI profile for the building. In this study, LCI profile results focus on the manufacturing and transportation of materials and their installation in to the initial structure and envelope assemblies. As this study is a cradle-to-gate assessment, the expected service life of the [*insert Building Name*] building is set to 1 year, which results in the maintenance, operating energy and end-of-life stages of the building's life-cycle being left outside the scope of assessment.

The IE then filters the LCA results through a set of characterization measures based on the mid-point impact assessment methodology developed by the US Environmental Protection Agency (US EPA), the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) version 2.2. In order to generate a complete environmental impact profile for the [*insert Building Name*] building, all of the available TRACI impact assessment categories available in the IE are included in this study, and are listed as;

- Global warming potential
- Acidification potential
- Eutrophication potential
- Ozone depletion potential
- Photochemical smog potential
- Human health respiratory effects potential
- Weighted raw resource use
- Primary energy consumption

Using the summary measure results, a sensitivity analysis is then conducted in order to reveal the effect of material changes on the impact profile of the [*insert Building Name*] building. Finally, using the UBC Residential Environmental Assessment Program (REAP) as a guide, this study then estimates the embodied energy involved in upgrading the insulation and window R-values to REAP standards and calculates the energy payback period of investing in a better performing envelope.

The primary sources of data for this LCA are the original architectural and structural drawings from when the [*insert Building Name*] building was initially constructed in [*insert year building was constructed in*]. The assemblies of the building that are modeled include the foundation, columns and beams, floors, walls and roofs, as well as the associated envelope and openings (ie. doors and windows) within each of these assemblies. The decision to omit other building components, such as flooring, electrical aspects, HVAC system, finishing and detailing, etc., are associated with the limitations of available data and the IE software, as well as to minimize the uncertainty of the model. In the analysis of these assemblies, some of the drawings lack sufficient material details, which necessitate the usage of assumptions to complete the modeling of the building in the IE software. Furthermore, there are inherent assumptions made by the IE software in order to generate the bill of materials and limitations to what it can model, which necessitated further assumptions to be made. These assumptions and limitation will be discussed further as they energy in the Building Model section and, as previously mentioned, all specific input related assumption are to be contained in the Input Assumptions document.

Academic Buildings - Net Bill of Materials

The following are the resulting Net Bill of Materials generated from the respective Academic Building LCA models. These are calculated from the Gross Bill of Materials by subtracting out Construction Wastes, which are calculated using Construction Waste Factors specific to each construction material. The tool used to develop the Academic Building LCA models in (the Impact Estimator or IE) outputs a Gross Bill of Materials, which is a list of those construction materials and the amount used to construct the building and is inclusive of those materials wasted in the construction of the building (Construction Wastes). The following three steps are used to calculate the Net Bill of Materials, by weight, from the Gross Bill of Materials;

1. Convert construction material units to kilograms
2. Calculate Construction Wastes using Construction Waste Factors
3. Subtract Constructed Wastes from Gross Bill of Materials

The following series of tables contain the Net Bill of Material, by weight, results for each of the Academic Building as well as the total for all UBC Academic Buildings.

B.5 UBC-LCA data base summary

The following tables show a summary of the key data metric in the database. These included aggregated data and results from individual buildings.

Table B-7 Bill of materials summary.

Construction Material	Units	UBC Academic Building Average	UBC Academic Building Total
#15 Organic Felt	kg	3,657.41	73,148.18
1/2" Fire-Rated Type X Gypsum Board	kg	1,401.77	1,401.77
1/2" Gypsum Fibre Gypsum Board	kg	79,090.00	237,269.99
1/2" Moisture Resistant Gypsum Board	kg	14,160.97	99,126.82
1/2" Regular Gypsum Board	kg	171,087.66	2,908,490.18
3 mil Polyethylene	kg	275.31	2,477.76
6 mil Polyethylene	kg	640.63	14,734.54
5/8" Fire-Rated Type X Gypsum Board	kg	52,208.63	156,625.90
5/8" Gypsum Fibre Gypsum Board	kg	31,128.43	31,128.43
5/8" Moisture Resistant Gypsum Board	kg	44,346.22	88,692.44
5/8" Regular Gypsum Board	kg	109,773.68	1,207,510.51
Aluminum	kg	17,018.60	493,539.40
Ballast (aggregate stone)	kg	113,464.22	2,496,212.94
Batt. Fiberglass	kg	27,489.16	604,761.57
Batt. Rockwool	kg	6,879.64	27,518.55
Blown Cellulose	kg	1,711.00	10,266.02
Brick Type 2	kg		
Cedar Wood Shiplap Siding	kg	27,799.05	55,598.10
Cold Rolled Sheet	kg	516.67	6,716.66
Commercial(26 ga.) Steel Cladding	kg	11,646.03	93,168.28
Concrete 20 MPa (flyash av)	kg	4,150,698.99	87,164,678.73
Concrete 30 MPa (flyash av)	kg	6,004,755.40	174,137,906.54
Concrete 60 MPa (flyash av)	kg	1,668,550.99	18,354,060.92
Concrete 20 MPa (flyash 25%)	kg		
Concrete 30 MPa (flyash 25%)	kg	5,243,572.50	5,243,572.50
Concrete 60 MPa (flyash 25%)	kg		
Concrete Blocks	kg	703,286.18	12,659,151.21
Concrete Brick	kg	271,301.53	1,627,809.20
EPDM membrane	kg	785.67	22,784.46
Expanded Polystyrene	kg	1,205.60	19,289.58
Extruded Polystyrene	kg	8,577.01	128,655.12
Foam Polyisocyanurate	kg	11,778.56	35,335.68
Galvanized Decking	kg	32,979.45	296,815.07
Galvanized Sheet	kg	5,019.77	140,553.47
Galvanized Studs	kg	80,105.03	961,260.30
Glazing Panel	kg	329.18	6,583.69
GluLam Sections	kg		
Hollow Structural Steel	kg	9,558.85	66,911.92
Hot Rolled Sheet	kg	1.49	1.49
Isocyanurate	kg	5,542.20	11,084.39
Joint Compound	kg	20,893.74	522,343.43
Laminated Veneer Lumber	kg		
Large Dimension Softwood Lumber, Green	kg	16,645.37	33,290.73
Large Dimension Softwood Lumber, kiln-dried	kg	52,921.28	105,842.57
Low E Tin Glazing	kg	4,808.76	19,235.03
Metric Modular (Modular) Brick	kg	481,729.21	2,408,646.03
Modified Bitumen membrane	kg	9,459.47	132,432.64
Mortar	kg	197,495.15	4,344,893.29
Nails	kg	2,691.33	78,048.53
Ontario (Standard) Brick	kg	293,345.55	586,691.11
Open Web Joists	kg	20,557.39	164,459.10
Oriented Strand Board	kg	53,593.78	214,375.14
Paper Tape	kg	244.97	6,124.18
Parallel Strand Lumber	kg	66,886.41	66,886.41
Pine Wood Bevel Siding	kg		
Polyester felt	kg		
Polyethylene Filter Fabric	kg	9,091.17	54,547.02
PVC membrane	kg	7,012.81	14,025.62
Rebar, Rod, Light Sections	kg	243,001.17	7,047,034.04
Residential(30 ga.) Steel Cladding	kg	910.80	910.80
Roofing Asphalt	kg	22,491.77	472,327.26
Screws Nuts & Bolts	kg	2,685.09	51,016.76
Small Dimension Softwood Lumber, Green	kg	26,175.60	157,053.59
Small Dimension Softwood Lumber, kiln-dried	kg	16,152.62	419,968.02
Softwood Plywood	kg	9,055.32	108,663.89
Solvent Based Alkyd Paint	kg	51.38	1,130.31
Solvent Based Varnish	kg	228.68	457.37
Split-faced Concrete Block	kg	836,280.06	836,280.06
Standard Glazing	kg	15,231.09	350,314.99
Steel Tubing	kg	297.50	297.50
Stucco over metal mesh	kg	51,386.13	154,158.40
Stucco over porous surface	kg	132,154.06	528,616.24
Type III Glass Felt	kg	3,884.58	50,499.48
Vinyl Siding	kg	16,967.44	16,967.44
Water Based Latex Paint	kg	267.95	7,234.77
Welded Wire Mesh / Ladder Wire	kg	5,324.37	154,406.64
Wide Flange Sections	kg	117,787.26	706,723.58
Wood Frame	kg		

Material	Units	Curtis	Buchanan All	hemistry - Sou	hemistry - No	Lasserre	Scarfe
#15 Organic Felt	kg	3,642.74	7,255.27	1,719.78		1,510.26	1,931.03
1/2" Fire-Rated Type X Gypsum Board	kg						
1/2" Gypsum Fibre Gypsum Board	kg		100,435.08			125,449.14	
1/2" Moisture Resistant Gypsum Board	kg		45,224.12			9,413.87	
1/2" Regular Gypsum Board	kg	31,481.57		25,165.76			
3 mil Polyethylene	kg		72.02	139.99		51.41	
6 mil Polyethylene	kg		1,077.38	292.07	587.82	25.07	639.10
5/8" Fire-Rated Type X Gypsum Board	kg						
5/8" Gypsum Fibre Gypsum Board	kg						
5/8" Moisture Resistant Gypsum Board	kg						
5/8" Regular Gypsum Board	kg						11,186.46
Aluminum	kg	4,004.20	43,664.30	10,378.20	3,505.30	7,983.90	760.60
Ballast (aggregate stone)	kg	43,851.20		23,975.78		21,054.80	26,920.86
Batt. Fiberglass	kg		15.83	1,916.95		3,894.12	12.89
Batt. Rockwool	kg		1,832.05				
Blown Cellulose	kg	18.10		3,071.23			1,724.24
Brick Type 2	kg						
Cedar Wood Shiplap Siding	kg						
Cold Rolled Sheet	kg	15.15		430.95	137.31	387.59	
Commercial(26 ga.) Steel Cladding	kg						
Concrete 20 MPa (flyash av)	kg	2,157,140.57	26,293.18		1,620,509.07	2,082,971.85	
Concrete 30 MPa (flyash av)	kg	202,686.61	21,512,200.80	6,084,522.70	1,963,548.93	3,081,220.61	6,213,305.63
Concrete 60 MPa (flyash av)	kg	83,309.85				2,316,495.92	
Concrete 20 MPa (flyash 25%)	kg						
Concrete 30 MPa (flyash 25%)	kg						
Concrete 60 MPa (flyash 25%)	kg						
Concrete Blocks	kg		883,023.55	273,588.83	157,749.81	942,935.03	41,694.54
Concrete Brick	kg	17,387.12		494,455.82	157,557.99	444,657.09	
EPDM membrane	kg	246.07	2,588.12	185.49	224.05	298.91	395.57
Expanded Polystyrene	kg	1,559.48		2,136.29			10.92
Extruded Polystyrene	kg		12,884.07		7,375.02		2,828.69
Foam Polyisocyanurate	kg				908.56		
Galvanized Decking	kg	21,261.24					
Galvanized Sheet	kg	3,236.41	1,969.21	2,484.21	3,187.31	1,244.93	1,963.76
Galvanized Studs	kg						
Glazing Panel	kg	4.75	183.17	432.71		3.16	3.00
GluLam Sections	kg						
Hollow Structural Steel	kg						
Hot Rolled Sheet	kg						
Isocyanurate	kg						
Joint Compound	kg	4,028.11	9,193.61	3,220.03		11,551.25	1,121.12
Laminated Veneer Lumber	kg						
Large Dimension Softwood Lumber, Green	kg						
Large Dimension Softwood Lumber, kiln-dried	kg						
Low E Tin Glazing	kg				4,656.10		
Metric Modular (Modular) Brick	kg						208,610.75
Modified Bitumen membrane	kg		43,811.05		331.74		
Mortar	kg	1,607.52	172,447.67	98,141.30	44,842.79	222,178.85	527,529.75
Nails	kg	1,635.81	6,972.55	1,027.33	525.35	1,143.63	1,383.71
Ontario (Standard) Brick	kg						
Open Web Joists	kg	33,241.73					
Oriented Strand Board	kg						
Paper Tape	kg	47.22	107.83	37.72		135.47	13.11
Parallel Strand Lumber	kg						
Pine Wood Bevel Siding	kg						
Polyester felt	kg						
Polyethylene Filter Fabric	kg						
PVC membrane	kg						
Rebar, Rod, Light Sections	kg	20,317.37	592,075.34	194,496.29	84,898.44	317,104.52	146,925.21
Residential(30 ga.) Steel Cladding	kg						
Roofing Asphalt	kg	29,575.55	37,520.37	16,170.53		14,200.46	18,156.84
Screws Nuts & Bolts	kg	2,575.84	141.81	334.46			
Small Dimension Softwood Lumber, Green	kg	2,699.42					1,258.11
Small Dimension Softwood Lumber, kiln-dried	kg	8,693.72	97,193.82	8,212.51		3,472.82	8,528.47
Softwood Plywood	kg		11,412.24				1,231.40
Solvent Based Alkyd Paint	kg	290.15		51.51	11.27		1.06
Solvent Based Varnish	kg						
Split-faced Concrete Block	kg						
Standard Glazing	kg		72,213.82	126.32		4,679.28	5,012.58
Steel Tubing	kg						
Stucco over metal mesh	kg	22,935.85					
Stucco over porous surface	kg						
Type III Glass Felt	kg	4,206.61		2,299.98		2,019.77	2,582.50
Vinyl Siding	kg						
Water Based Latex Paint	kg	85.83	204.95			44.80	79.67
Welded Wire Mesh / Ladder Wire	kg	2,528.79	3,063.28	594.47	436.39	16,636.68	1,774.58
Wide Flange Sections	kg	53,318.13					
Wood Frame	kg						

Material	Units	Hebb	Angus	MacMillan	Music	EOS - Main	EOS - South
#15 Organic Felt	kg	2,918.33	6,158.28	4,275.01	1,792.66		3,565.28
1/2" Fire-Rated Type X Gypsum Board	kg					1,401.77	
1/2" Gypsum Fibre Gypsum Board	kg						
1/2" Moisture Resistant Gypsum Board	kg						3,830.81
1/2" Regular Gypsum Board	kg	34,555.34	13,173.12		45,897.99		
3 mil Polyethylene	kg						
6 mil Polyethylene	kg	895.24		979.18		667.69	197.80
5/8" Fire-Rated Type X Gypsum Board	kg						
5/8" Gypsum Fibre Gypsum Board	kg						
5/8" Moisture Resistant Gypsum Board	kg						
5/8" Regular Gypsum Board	kg			82,704.41		116,604.12	
Aluminum	kg	7,182.20	26,973.30	30,783.50	5,951.90	9,589.60	6,453.40
Ballast (aggregate stone)	kg	53,231.69	123,975.02	59,598.62	24,991.72		2,216.93
Batt. Fiberglass	kg		3,428.74		7,978.32	5,207.31	
Batt. Rockwool	kg						
Blown Cellulose	kg						
Brick Type 2	kg						
Cedar Wood Shiplap Siding	kg						
Cold Rolled Sheet	kg	866.05		1,198.00			16.34
Commercial(26 ga.) Steel Cladding	kg		3,660.57			18,736.39	12,140.60
Concrete 20 MPa (flyash av)	kg		13,625,215.52	13,715,296.07	1,475,713.80	2,622,350.81	314,045.38
Concrete 30 MPa (flyash av)	kg	8,434,967.77	2,048,779.51	6,496,732.65	5,410,568.14	1,532,371.56	2,260,512.28
Concrete 60 MPa (flyash av)	kg		698,391.73	9,332,754.18			91,584.49
Concrete 20 MPa (flyash 25%)	kg						
Concrete 30 MPa (flyash 25%)	kg						
Concrete 60 MPa (flyash 25%)	kg						
Concrete Blocks	kg		6,882.22	3,774,545.07	160,293.56	269,775.04	
Concrete Brick	kg						
EPDM membrane	kg	459.05	1,289.02	1,491.24	351.03	612.92	412.47
Expanded Polystyrene	kg	4.45	425.61	8.91	3,601.54	26.72	11.13
Extruded Polystyrene	kg	15,657.49	2,169.60	10,921.09			
Foam Polyisocyanurate	kg						
Galvanized Decking	kg			5,557.56		64,073.49	
Galvanized Sheet	kg	1,786.36	2,750.02	7,498.56	1,752.00	13,553.30	4,693.99
Galvanized Studs	kg					33,009.27	
Glazing Panel	kg		11.07	350.60	16.97	0.62	
GluLam Sections	kg						
Hollow Structural Steel	kg					17,233.92	2,956.64
Hot Rolled Sheet	kg						
Isocyanurate	kg						2,163.32
Joint Compound	kg	4,421.41	522.10	8,288.81	5,872.67	11,863.08	
Laminated Veneer Lumber	kg						
Large Dimension Softwood Lumber, Green	kg						
Large Dimension Softwood Lumber, kiln-dried	kg						
Low E Tin Glazing	kg					8,731.08	
Metric Modular (Modular) Brick	kg			967,693.90			
Modified Bitumen membrane	kg			470.32		1,806.20	19,051.77
Mortar	kg	137,153.50	1,317.57	913,071.47	30,822.71	51,765.63	
Nails	kg	1,285.54	1,752.60	3,750.41	1,680.72	1,159.44	625.84
Ontario (Standard) Brick	kg	522,688.85					
Open Web Joists	kg			2,261.16		49,582.37	
Oriented Strand Board	kg						
Paper Tape	kg	51.87	6.08	97.19	68.88	139.08	
Parallel Strand Lumber	kg						
Pine Wood Bevel Siding	kg						
Polyester felt	kg						
Polyethylene Filter Fabric	kg	52.87	173.94				
PVC membrane	kg						
Rebar, Rod, Light Sections	kg	223,154.02	388,056.54	353,634.53	163,966.28	120,380.24	44,820.47
Residential(30 ga.) Steel Cladding	kg						
Roofing Asphalt	kg	15,173.25	15,340.61	40,196.44	16,855.73		17,050.50
Screws Nuts & Bolts	kg			824.60	6,004.88	20,629.86	12.22
Small Dimension Softwood Lumber, Green	kg				30,302.58		
Small Dimension Softwood Lumber, kiln-dried	kg	3,991.72	3,628.25	9,859.58	3,512.70	743.73	
Softwood Plywood	kg						
Solvent Based Alkyd Paint	kg	331.59	1.08	28.08	0.87	107.64	6.07
Solvent Based Varnish	kg						435.05
Split-faced Concrete Block	kg						
Standard Glazing	kg	10,781.03	11,312.01	22,706.03		353.59	10,520.78
Steel Tubing	kg						297.50
Stucco over metal mesh	kg						
Stucco over porous surface	kg						
Type III Glass Felt	kg	1,495.67		5,717.25	2,397.44		
Vinyl Siding	kg		16,967.44				
Water Based Latex Paint	kg	51.49	101.43	127.18	45.31	1,235.82	554.57
Welded Wire Mesh / Ladder Wire	kg	1,681.29	5,149.12	50,434.43	2,280.56	2,588.47	1,059.67
Wide Flange Sections	kg			10,905.15	117,699.12	366,174.47	
Wood Frame	kg						

Material	Units	CEME	Curtis Addition	FNH	Kenny	Chem Physics	ICICS/CS
#15 Organic Felt	kg	5,783.13	4,217.62	2,030.07		1,691.39	7,405.16
1/2" Fire-Rated Type X Gypsum Board	kg						
1/2" Gypsum Fibre Gypsum Board	kg					11,385.77	
1/2" Moisture Resistant Gypsum Board	kg				14,464.89	10,542.88	11,547.10
1/2" Regular Gypsum Board	kg	89,625.97		25,528.42	237,958.54		12,643.69
3 mil Polyethylene	kg	35.02				37.36	49.70
6 mil Polyethylene	kg		64.83	953.65	599.24	522.04	962.53
5/8" Fire-Rated Type X Gypsum Board	kg		401.06	73,345.09		82,879.75	
5/8" Gypsum Fibre Gypsum Board	kg					31,128.43	
5/8" Moisture Resistant Gypsum Board	kg				4,521.08		
5/8" Regular Gypsum Board	kg	1,462.30	82,793.34				198,719.78
Aluminum	kg	11,617.70	13,000.00	13,235.00	21,994.30	26,055.20	28,333.30
Ballast (aggregate stone)	kg	80,623.58	58,805.00	28,301.55	1,695.75	72,376.56	133,945.30
Batt. Fiberglass	kg	4,963.98	706.80	7,762.73	7,122.07	748.81	19,418.04
Batt. Rockwool	kg					2,168.53	
Blown Cellulose	kg			3,568.26		354.32	
Brick Type 2	kg						
Cedar Wood Shiplap Siding	kg						
Cold Rolled Sheet	kg						13.27
Commercial(26 ga.) Steel Cladding	kg				5,773.00	7,500.00	12,815.87
Concrete 20 MPa (flyash av)	kg	4,619,095.26		3,233,897.14	1,346,846.72		357,038.92
Concrete 30 MPa (flyash av)	kg	3,295,493.87	11,507,587.50	4,426,246.65	9,213,200.73	11,808,148.24	17,046,305.32
Concrete 60 MPa (flyash av)	kg	1,443,904.93			1,741,012.07		
Concrete 20 MPa (flyash 25%)	kg						
Concrete 30 MPa (flyash 25%)	kg						
Concrete 60 MPa (flyash 25%)	kg						
Concrete Blocks	kg	687,062.86			116,598.58	23,650.36	347,993.24
Concrete Brick	kg						15,196.15
EPDM membrane	kg	742.55	158.11	798.28	1,093.19	1,186.64	1,052.74
Expanded Polystyrene	kg	53.43				1,092.71	73.47
Extruded Polystyrene	kg	13,540.03	5,445.21	13,929.69	7,533.18	4,285.23	21,753.61
Foam Polyisocyanurate	kg						
Galvanized Decking	kg	42,405.96	125,730.00		3,898.03		
Galvanized Sheet	kg	17,125.52	4,019.40	1,673.50	1,397.29	4,080.48	13,516.97
Galvanized Studs	kg	6,333.92	10,494.00	11,143.34	53,548.01	55,498.41	42,954.52
Glazing Panel	kg		516.36	22.94	236.23	241.75	203.93
GluLam Sections	kg						
Hollow Structural Steel	kg				10,748.93		5,236.90
Hot Rolled Sheet	kg					1.49	
Isocyanurate	kg						
Joint Compound	kg	11,449.60	8,332.80	10,463.34	32,508.80	11,473.97	22,855.59
Laminated Veneer Lumber	kg						
Large Dimension Softwood Lumber, Green	kg						
Large Dimension Softwood Lumber, kiln-dried	kg						
Low E Tin Glazing	kg						
Metric Modular (Modular) Brick	kg						
Modified Bitumen membrane	kg	496.26			17,982.92	10,132.00	444.45
Mortar	kg	131,991.16			22,382.23	4,527.93	68,477.41
Nails	kg	4,127.25	1,940.00	2,389.21	2,660.52	2,413.65	2,553.53
Ontario (Standard) Brick	kg				64,002.26		
Open Web Joists	kg	38,510.90			4,585.09		
Oriented Strand Board	kg	11,624.13				97,360.92	
Paper Tape	kg	134.24	97.85	122.65	381.14	134.52	268.00
Parallel Strand Lumber	kg						
Pine Wood Bevel Siding	kg						
Polyester felt	kg						
Polyethylene Filter Fabric	kg		53,757.00				188.00
PVC membrane	kg					5,786.34	
Rebar, Rod, Light Sections	kg	224,907.71	273,240.00	177,668.37	317,660.31	260,624.33	428,881.07
Residential(30 ga.) Steel Cladding	kg						
Roofing Asphalt	kg	54,376.78	39,700.00	19,088.10		8,746.94	16,574.33
Screws Nuts & Bolts	kg	490.72	683.85	555.03	2,454.49	1,944.85	3,066.36
Small Dimension Softwood Lumber, Green	kg						
Small Dimension Softwood Lumber, kiln-dried	kg	38,715.50	2,037.69	7,185.10	21,914.56	9,025.20	12,174.76
Softwood Plywood	kg		2,013.29			115.27	10,814.65
Solvent Based Alkyd Paint	kg	60.13	1.08		3.47	10.40	48.03
Solvent Based Varnish	kg						22.32
Split-faced Concrete Block	kg						
Standard Glazing	kg	9,578.83	1,337.45	14,007.40	11,732.12	28,061.59	16,139.71
Steel Tubing	kg						
Stucco over metal mesh	kg						46,116.61
Stucco over porous surface	kg						
Type III Glass Felt	kg	7,734.16	5,623.71	2,714.95			
Vinyl Siding	kg						
Water Based Latex Paint	kg	65.91	26.24	92.68	333.39	165.26	382.15
Welded Wire Mesh / Ladder Wire	kg	13,306.64	1,176.00	1,326.43	12,375.05	1,707.65	3,312.60
Wide Flange Sections	kg		140,580.00				18,046.71
Wood Frame	kg						

Material	Units	FSC	AERL	ChemBio	Kaiser
#15 Organic Felt	kg				
1/2" Fire-Rated Type X Gypsum Board	kg				
1/2" Gypsum Fibre Gypsum Board	kg				
1/2" Moisture Resistant Gypsum Board	kg			4,103.15	
1/2" Regular Gypsum Board	kg	73,121.63	729.63	1,878,099.45	1,731.53
3 mil Polyethylene	kg	1,500.00			
6 mil Polyethylene	kg	929.27	1,242.70	1,395.10	872.06
5/8" Fire-Rated Type X Gypsum Board	kg				
5/8" Gypsum Fibre Gypsum Board	kg				
5/8" Moisture Resistant Gypsum Board	kg		84,171.36		
5/8" Regular Gypsum Board	kg	250,461.42	74,792.09		189,331.88
Aluminum	kg	32,207.00	36,457.50	27,722.30	43,828.00
Ballast (aggregate stone)	kg	100,727.55			163,048.50
Batt. Fiberglass	kg	48,272.93	6,526.14	476,932.94	1,215.34
Batt. Rockwool	kg				
Blown Cellulose	kg				
Brick Type 2	kg				
Cedar Wood Shiplap Siding	kg				
Cold Rolled Sheet	kg	458.96	220.18	434.61	
Commercial(26 ga.) Steel Cladding	kg		618.50	31,923.36	
Concrete 20 MPa (flyash av)	kg	6,894,913.52	554,651.80	336,489.59	
Concrete 30 MPa (flyash av)	kg	11,326,893.42	5,356,479.16	16,168,041.17	9,031,137.00
Concrete 60 MPa (flyash av)	kg			659,576.93	
Concrete 20 MPa (flyash 25%)	kg				
Concrete 30 MPa (flyash 25%)	kg				5,243,572.50
Concrete 60 MPa (flyash 25%)	kg				
Concrete Blocks	kg		33,840.34	1,437,707.17	575,181.30
Concrete Brick	kg			498,555.03	
EPDM membrane	kg	1,575.35	665.64	818.91	777.70
Expanded Polystyrene	kg	7,194.81		3,045.59	
Extruded Polystyrene	kg		4,983.64	1,847.35	
Foam Polyisocyanurate	kg		24,326.05	10,101.07	
Galvanized Decking	kg	16,039.39		16,156.11	
Galvanized Sheet	kg	14,038.70	7,999.20	12,516.27	2,754.48
Galvanized Studs	kg	84,388.39	77,930.62	507,279.47	28,083.33
Glazing Panel	kg	407.32	1,372.82	645.25	1,707.89
GluLam Sections	kg				
Hollow Structural Steel	kg		14,353.12	5,993.36	10,389.06
Hot Rolled Sheet	kg				
Isocyanurate	kg				8,921.08
Joint Compound	kg	34,457.80	15,150.54	240,774.40	19,197.06
Laminated Veneer Lumber	kg				
Large Dimension Softwood Lumber, Green	kg				
Large Dimension Softwood Lumber, kiln-dried	kg				
Low E Tin Glazing	kg		3,118.13		2,729.73
Metric Modular (Modular) Brick	kg	40,825.33	115,339.95		
Modified Bitumen membrane	kg	4,688.12	6,780.16	1,163.10	23,136.44
Mortar	kg	188,637.44	39,551.52	321,587.56	110,323.20
Nails	kg	4,117.26	1,341.51	17,126.81	984.55
Ontario (Standard) Brick	kg				
Open Web Joists	kg	8,278.88		24,922.16	
Oriented Strand Board	kg	103,370.35		2,019.73	
Paper Tape	kg	403.94	177.65	2,822.83	225.06
Parallel Strand Lumber	kg	66,886.41			
Pine Wood Bevel Siding	kg				
Polyester felt	kg				
Polyethylene Filter Fabric	kg				226.71
PVC membrane	kg	8,239.28			
Rebar, Rod, Light Sections	kg	457,325.65	145,656.52	396,819.72	407,276.10
Residential(30 ga.) Steel Cladding	kg			910.80	
Roofing Asphalt	kg				
Screws Nuts & Bolts	kg	3,057.93	2,498.14	1,450.44	2,851.12
Small Dimension Softwood Lumber, Green	kg			804.28	
Small Dimension Softwood Lumber, kiln-dried	kg	19,484.75		189.08	1,184.92
Softwood Plywood	kg	9,884.11	306.06	1,231.73	8,701.74
Solvent Based Alkyd Paint	kg	91.71	18.77	57.79	5.06
Solvent Based Varnish	kg				
Split-faced Concrete Block	kg	836,280.06			
Standard Glazing	kg	28,841.52		12,400.76	
Steel Tubing	kg				
Stucco over metal mesh	kg				
Stucco over porous surface	kg				
Type III Glass Felt	kg				
Vinyl Siding	kg				
Water Based Latex Paint	kg	227.07	5.43	286.48	96.80
Welded Wire Mesh / Ladder Wire	kg	5,757.79	1,905.22	4,335.91	2,792.02
Wide Flange Sections	kg				
Wood Frame	kg				

The Net Bill of Materials shown previously in Table B.7 has been collated into Material Categories using the categorizations shown Table B.8.

Table B-8 Material category summary.

Material Category	Units	UBC Academic Building Total
Wood	kg	1,161,678
Wall Coverings	kg	5,258,714
Metal	kg	10,194,952
Roof Materials	kg	3,315,978
Masonry/Bricks	kg	22,463,471
Concrete	kg	285,582,993
Insulation	kg	836,911
Glass	kg	376,134
Plastics	kg	34,180
Miscellaneous	kg	8,822
Total	**kg**	**329,233,832**

Material Category	Units	Chemistry	Geography	Math	Henn	Klink	Wesbrook	EOS - East	Curtis	Buchanan All
Wood	kg	13,972	230,402	170,122	71,646	10,002	8,862	34,887	11,393	108,606
Wall Coverings	kg	-	83,022	51,113	180,179	116,965	263,202	-	35,557	154,961
Metal	kg	323,090	16,316	11,327	277,820	359,300	439,865	69,578	142,135	647,887
Roof Materials	kg	1,351,720	89,038	5,206	136,342	2,593	3,893	40,289	81,522	91,175
Masonry/Bricks	kg	3,001,168	-	-	-	-	1,770,857	487,317	18,995	1,055,471
Concrete	kg	6,208,468	543,829	504,371	11,535,095	11,022,629	12,856,795	1,828,732	2,466,073	21,538,494
Insulation	kg	8,940	1,564	15	15,359	7,812	-	3,541	1,578	14,732
Glass	kg	-	10,513	5,294	14,531	34,859	22,340	3,197	5	72,397
Plastics	kg	383	373	-	574	334	590	170	-	1,149
Miscellaneous	kg	1,103	479	858	94	75	118	301	376	205
Total	**kg**	**10,908,844**	**975,534**	**748,306**	**12,231,642**	**11,554,570**	**15,366,520**	**2,468,012**	**2,757,633**	**23,685,077**

Material Category	Units	Chemistry - South	Chemistry - North	Lasserre	Scarfe	Hebb	Angus	MacMillan	Music	EOS - Main
Wood	kg	8,213	-	3,473	11,018	3,992	3,628	9,860	33,815	744
Wall Coverings	kg	28,424	-	146,550	12,321	39,029	13,701	91,090	51,840	130,008
Metal	kg	209,746	92,690	344,501	152,808	235,955	428,342	466,848	299,335	699,477
Roof Materials	kg	44,352	556	39,084	49,987	73,331	146,937	111,749	46,389	2,419
Masonry/Bricks	kg	866,186	360,151	1,609,771	777,835	659,842	8,200	5,655,310	191,116	321,541
Concrete	kg	6,084,523	3,584,058	7,480,688	6,213,306	8,434,968	16,372,387	29,544,783	6,886,282	4,154,722
Insulation	kg	7,124	8,284	3,894	4,577	15,662	6,024	10,930	11,580	5,234
Glass	kg	559	4,656	4,682	5,016	10,781	11,323	23,057	17	9,085
Plastics	kg	432	588	76	639	895	16,967	979	-	668
Miscellaneous	kg	52	11	45	81	383	103	155	46	1,343
Total	**kg**	**7,249,609**	**4,050,993**	**9,632,765**	**7,227,586**	**9,474,838**	**17,007,612**	**35,914,761**	**7,520,420**	**5,325,241**

Material Category	Units	EOS - South	CEME	Curtis Addition	FNH	Kenny	Chem Physics	ICICS/CS	FSC	AERL
Wood	kg	-	50,340	4,051	7,185	21,915	106,501	22,989	199,626	306
Wall Coverings	kg	3,831	102,672	91,625	109,459	289,834	147,545	246,034	358,445	175,021
Metal	kg	70,120	358,826	570,863	207,991	426,346	359,826	553,494	625,670	274,627
Roof Materials	kg	42,297	149,756	162,261	52,933	20,772	99,920	159,610	115,230	7,446
Masonry/Bricks	kg	-	819,054	-	-	202,983	28,178	431,667	1,065,743	188,732
Concrete	kg	2,666,142	9,358,494	11,507,588	7,660,144	12,301,060	11,808,148	17,449,461	18,221,807	5,911,131
Insulation	kg	2,174	18,557	6,152	25,261	14,655	8,650	41,245	55,468	35,836
Glass	kg	10,521	9,579	1,854	14,030	11,968	28,303	16,344	29,249	4,491
Plastics	kg	198	35	65	954	599	559	1,012	2,429	1,243
Miscellaneous	kg	996	126	27	93	337	176	453	319	24
Total	**kg**	**2,796,279**	**10,867,440**	**12,344,486**	**8,078,050**	**13,290,469**	**12,587,807**	**18,922,309**	**20,673,985**	**6,598,857**

Material Category	Units	ChemBio	Kaiser
Wood	kg	4,245	9,887
Wall Coverings	kg	2,125,800	210,486
Metal	kg	1,041,598	488,570
Roof Materials	kg	1,982	187,189
Masonry/Bricks	kg	2,257,850	685,505
Concrete	kg	17,164,108	14,274,710
Insulation	kg	491,927	10,136
Glass	kg	13,046	4,438
Plastics	kg	1,395	872
Miscellaneous	kg	344	102
Total	**kg**	**23,102,294**	**15,871,893**

Academic Buildings - Impact Assessment Profiles

The life-cycle impact assessment (LCIA) profiles that resulted from the LCA models of the UBC Academic Buildings are shown in Table B.9. These include the Total impact (i.e. sum of all UBC Academic Buildings modeled), as well as per building constructed. It is important to consider these results in conjunction with the Goal and Scope when interpreting their meaning.

Table B-9 LCIA summary.

Impact Category	Units	UBC Academic Building Total
Primary Energy Consumption	MJ	7.41E+08
Weighted Resource Use	kg	4.24E+08
Global Warming Potential	kg CO2 eq	6.34E+07
Acidification Potential	moles of H+ eq	2.64E+07
HH Respiratory Effects Potential	kg PM2.5 eq	2.11E+05
Eutrophication Potential	kg N eq	2.56E+04
Ozone Depletion Potential	kg CFC-11 eq	1.42E-01
Smog Potential	kg NOx eq	3.04E+05

Impact Category	Units	Chemistry	Geography	Math	Henn	Klink	Wesbrook	EOS - East
Primary Energy Consumption	MJ	1.69E+07	6.52E+06	2.28E+06	2.60E+07	1.75E+07	3.07E+07	7.82E+06
Weighted Resource Use	kg	8.83E+06	1.64E+06	1.26E+06	1.67E+07	1.37E+07	1.85E+07	2.83E+06
Global Warming Potential	kg CO2 eq	1.39E+06	3.37E+05	1.57E+05	2.10E+06	1.60E+06	2.37E+06	5.89E+05
Acidification Potential	moles of H+ eq	5.95E+05	1.67E+05	7.34E+04	9.81E+05	6.49E+05	1.09E+06	2.71E+05
HH Respiratory Effects Potential	kg PM2.5 eq	5.11E+03	1.50E+03	7.88E+02	8.74E+03	5.81E+03	8.48E+03	1.98E+03
Eutrophication Potential	kg N eq	7.12E+02	1.04E+02	6.10E+01	9.58E+02	7.70E+02	1.16E+03	2.42E+02
Ozone Depletion Potential	kg CFC-11 eq	2.87E-03	6.04E-03	2.56E-03	3.67E-03	2.57E-03	3.43E-03	2.47E-03
Smog Potential	kg NOx eq	6.96E+03	1.52E+03	7.58E+02	1.23E+04	7.83E+03	1.20E+04	3.57E+03

Impact Category	Units	Curtis	Buchanan All	Chemistry - South	Chemistry - North	Lasserre	Scarfe	Hebb
Primary Energy Consumption	MJ	9.79E+06	4.59E+07	1.36E+07	6.57E+06	1.93E+07	1.35E+07	1.93E+07
Weighted Resource Use	kg	3.50E+06	2.82E+07	8.77E+06	4.60E+06	1.07E+07	8.89E+06	1.16E+07
Global Warming Potential	kg CO2 eq	6.20E+05	4.06E+06	1.23E+06	5.85E+05	1.59E+06	1.23E+06	1.63E+06
Acidification Potential	moles of H+ eq	2.37E+05	1.75E+06	5.10E+05	2.40E+05	6.46E+05	5.15E+05	7.05E+05
HH Respiratory Effects Potential	kg PM2.5 eq	1.63E+03	1.43E+04	4.06E+03	1.79E+03	4.76E+03	3.34E+03	4.88E+03
Eutrophication Potential	kg N eq	2.35E+02	1.84E+03	5.42E+02	2.58E+02	7.70E+02	4.64E+02	6.66E+02
Ozone Depletion Potential	kg CFC-11 eq	7.05E-04	8.81E-03	2.13E-03	8.75E-04	2.38E-03	2.34E-03	2.47E-03
Smog Potential	kg NOx eq	2.68E+03	2.22E+04	6.14E+03	3.33E+03	7.62E+03	6.37E+03	8.92E+03

Impact Category	Units	Angus	MacMillan	Music	EOS - Main	EOS - South	CEME	Curtis Addition
Primary Energy Consumption	MJ	2.54E+07	5.45E+07	1.65E+07	2.63E+07	5.90E+06	2.65E+07	3.30E+07
Weighted Resource Use	kg	1.98E+07	3.92E+07	9.14E+06	7.35E+06	3.44E+06	1.27E+07	1.56E+07
Global Warming Potential	kg CO2 eq	2.25E+06	5.27E+06	1.33E+06	1.67E+06	5.19E+05	1.98E+06	2.54E+06
Acidification Potential	moles of H+ eq	9.83E+05	2.23E+06	5.19E+05	5.41E+05	2.19E+05	8.09E+05	9.72E+05
HH Respiratory Effects Potential	kg PM2.5 eq	7.12E+03	1.63E+04	3.60E+03	4.08E+03	1.75E+03	5.89E+03	7.07E+03
Eutrophication Potential	kg N eq	9.82E+02	1.78E+03	6.08E+02	8.75E+02	2.14E+02	8.11E+02	1.08E+03
Ozone Depletion Potential	kg CFC-11 eq	5.58E-03	8.47E-03	1.95E-03	1.50E-03	1.00E-03	4.15E-03	3.19E-03
Smog Potential	kg NOx eq	1.11E+04	2.84E+04	6.20E+03	4.92E+03	2.75E+03	1.00E+04	1.21E+04

Impact Category	Units	FNH	Kenny	Chem Physics	ICICS/CS	FSC	AERL	ChemBio
Primary Energy Consumption	MJ	1.59E+07	5.77E+07	2.55E+07	3.73E+07	5.93E+07	1.86E+07	7.32E+07
Weighted Resource Use	kg	9.76E+06	3.75E+07	1.60E+07	2.32E+07	3.48E+07	8.56E+06	2.85E+07
Global Warming Potential	kg CO2 eq	1.33E+06	5.40E+06	2.24E+06	3.31E+06	5.70E+06	1.63E+06	5.97E+06
Acidification Potential	moles of H+ eq	5.75E+05	2.26E+06	9.56E+05	1.37E+06	2.30E+06	6.63E+05	2.37E+06
HH Respiratory Effects Potential	kg PM2.5 eq	4.62E+03	1.69E+04	7.76E+03	1.07E+04	1.82E+04	6.44E+03	2.25E+04
Eutrophication Potential	kg N eq	5.88E+02	2.09E+03	9.97E+02	1.45E+03	1.63E+03	6.46E+02	1.85E+03
Ozone Depletion Potential	kg CFC-11 eq	2.11E-03	1.17E-02	1.00E-02	6.05E-03	3.09E-02	1.67E-03	6.21E-03
Smog Potential	kg NOx eq	7.69E+03	2.55E+04	1.21E+04	1.76E+04	1.96E+04	7.79E+03	2.19E+04

Impact Category	Units	Kaiser
Primary Energy Consumption	MJ	2.96E+07
Weighted Resource Use	kg	1.90E+07
Global Warming Potential	kg CO2 eq	2.75E+06
Acidification Potential	moles of H+ eq	1.15E+06
HH Respiratory Effects Potential	kg PM2.5 eq	1.06E+04
Eutrophication Potential	kg N eq	1.26E+03
Ozone Depletion Potential	kg CFC-11 eq	4.21E-03
Smog Potential	kg NOx eq	1.41E+04

The Academic Building LCIA profiles have also been equated such that impacts are allocated across each square foot academic building floor area constructed using the building square footage references in Table B.10.

Table B-10 Building characteristics summary.

Measurement	Units	Chemistry	Geography	Math	Henn	Klink	Wesbrook	EOS - East	Curtis	Buchanan All
Year of Construction		1925	1925	1925	1945	1947	1949	1950	1950	1958, 1960
Total Square Foot Area	sq.ft	78,458.14	51,459.00	28,580.00	109,324.00	95,615.00	98,705.00	30,252.00	29,558.00	190,796.00

Measurement	Units	Chemistry - South	Chemistry - North	Lasserre	Scarfe	Hebb	Angus	MacMillan	Music	EOS - Main
Year of Construction		1959	1962	1962	1962	1964	1965	1967	1967	1971
Total Square Foot Area	sq.ft	58,071.00	25,989.00	54,544.00	70,127.00	66,966.18	124,268.00	151,629.00	83,454.00	97,392.00

Measurement	Units	EOS - South	CEME	Curtis Addition	FNH	Kenny	Chem Physics	ICICS/CS	FSC	AERL
Year of Construction		1974	1976	1976	1982	1983	1989	1993	1998	2005
Total Square Foot Area	sq.ft	16,846.00	111,159.00	75,195.00	55,509.00	93,964.85	85,756.07	104,528.33	165,222.81	57,325.00

Measurement	Units	ChemBio	Kaiser
Year of Construction		2005	2005
Total Square Foot Area	sq.ft	119,330.00	134,927.00

In a LCA, functional units are used to express the life-cycle impacts created by products with the function(s) they serve. There are ongoing discussions regarding the use of functional units to express the LCA results of buildings, as they are products that serve a broad range of functions. That is, it is difficult to determine functional units that capture a broad range of building functions appropriately. This difficulty is also a discussion topic in determining appropriate and fair units to base comparative assertions between building LCA results on. To contribute to further research and discussions in this area of defining appropriate functional units for building LCAs, the UBC Academic Building Functional Area Types are shown in Table B.11 as a percentage of total building square foot area.

Table B-11 Functional area summary.

Functional Area Type	Chemistry	Geography	Math	Henn	Klink	Wesbrook	EOS - East
Classrooms	2.1%	21.3%	37.7%		25.4%	5.8%	19.8%
Offices/Office Spaces	2.1%	8.0%	12.7%		2.5%	10.4%	8.7%
Testing labs	45.4%	26.0%			19.0%	8.7%	28.4%
Library		4.7%			3.8%	2.2%	5.1%
Study/Research/Prep/Computer lab rooms	6.4%	10.3%	5.9%		4.0%	18.9%	11.3%
Storage rooms	2.0%	5.2%	0.5%		7.1%	4.3%	5.7%
Stairwells/Halls/ Atriums	21.5%	14.7%	22.2%		21.8%	37.7%	16.0%
Washrooms/ Locker rooms	6.3%	4.7%	11.4%		1.8%	6.0%	5.2%
Mechanical rooms	3.8%				6.5%	3.0%	
Auditorium/ Lecture Halls	10.4%	5.1%	9.5%		8.1%	3.0%	

Functional Area Type	Curtis	Buchanan All	emistry - So	emistry - No	Lasserre	Scarfe	Hebb
Classrooms	8.6%				10.2%	14.5%	
Offices/Office Spaces	5.2%		4.6%	12.4%	12.0%	4.3%	
Testing labs			41.9%	29.3%		15.0%	44.3%
Library	6.7%					3.4%	
Study/Research/Prep/Computer lab rooms	45.5%			40.8%	33.4%	12.4%	12.6%
Storage rooms	7.5%			2.5%	2.2%	10.6%	1.0%
Stairwells/Halls/ Atriums	11.4%		29.3%	13.5%	28.1%	24.1%	23.3%
Washrooms/ Locker rooms	8.4%		4.6%	1.0%	3.7%	2.1%	3.2%
Mechanical rooms	6.7%		1.9%	0.6%	0.4%	8.2%	6.8%
Auditorium/ Lecture Halls			17.7%		10.1%	5.5%	8.9%

Functional Area Type	Angus	MacMillan	Music	EOS - Main	EOS - South	CEME	Curtis Addition
Classrooms	21.5%		3.6%	20.8%			
Offices/Office Spaces	16.3%		20.5%	4.6%	60.8%		12.9%
Testing labs				15.2%			
Library			10.4%	6.2%			47.5%
Study/Research/Prep/Computer lab rooms	2.9%		10.5%	18.7%			5.7%
Storage rooms	7.0%		5.2%	3.7%	29.4%		0.7%
Stairwells/Halls/ Atriums	39.4%		23.7%	26.5%	5.4%		20.1%
Washrooms/ Locker rooms	1.4%		2.6%	1.4%	3.3%		2.0%
Mechanical rooms	1.9%		9.1%	2.9%	1.1%		4.1%
Auditorium/ Lecture Halls	9.5%		14.2%				6.9%

Functional Area Type	FNH	Kenny	Chem Physic	ICICS/CS	FSC	AERL	ChemBio
Classrooms	12.1%	9.6%		4.2%	7.7%	3.0%	0.9%
Offices/Office Spaces	12.1%	17.9%	14.5%	26.5%	23.7%	30.8%	9.6%
Testing labs	20.3%	26.1%	49.6%	18.2%	13.5%	2.2%	33.5%
Library		1.1%				1.5%	
Study/Research/Prep/Computer lab rooms	10.5%	2.4%	4.6%	20.0%	14.1%	10.1%	12.3%
Storage rooms	4.0%	4.4%	2.4%	0.9%	1.1%	1.2%	11.6%
Stairwells/Halls/ Atriums	33.4%	29.7%	18.6%	24.8%	29.3%	35.7%	23.1%
Washrooms/ Locker rooms	2.7%	2.2%	1.3%	1.9%	1.8%	2.7%	2.7%
Mechanical rooms	5.1%	5.9%	9.1%	3.4%	8.7%	9.0%	2.0%
Auditorium/ Lecture Halls	0.0%	0.8%				3.8%	4.2%

Appendix C Operational performance data

C.1 Supplementary data (metered building scale)

All buildings with major renovations are considered as ‘new construction’ during the data analysis. Also to consider are the occasional mismatches in metered areas. In these cases, consumption is normalized to the nominal building area, however this introduces errors if the building areas being metered (or unmetered) are programmatically different from the nominal area. In these cases, each building was examined on a case-by-case basis to check for mismatches. Ambiguous metering areas were removed from the database

Table C-1 Energy metering data for 2010-2011.

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					Electricity Metered Data			Steam Metered Data		
Building Name	**LEED Equiv?**	**Category**	**Year of Construction**	**Year of Renovation**	**Metered Area (m2)**	**Annual Consumption (kWh)**	**Elec BEPI (kWh/m2)**	**Metered Area (m2)**	**Annual Consumption (kWh)**	**Steam BEPI (kWh/m2)**
George F Curtis		Classroom	1976		17773	1889013	106	9708	599994	62
AERL	Y	Classroom	2005		6031	577978	96	6031	422445	70
Mathematics		Classroom	1925		7680	1300672	169			
Geography		Classroom	1925		5925	301084	51			
Neville Scarfe		Classroom	1962		19945	1546004	78	19945	1981997	99
West Mall Swing Space	Y	Classroom	2005		5399	434284	80			
Buchanan A, B & C		Classroom	1958	2010	10731	658355	61			
Anthropology and Sociology Complex		Classroom	1975		7630	525294	69			
Jack Bell		Classroom	1992		2930	262188	89			
Instructional Resources Centre		Classroom	1972		11687	1058848	91	11687	862031	74
Henry Angus Addition		Classroom	1976		13068	1307874	100	13068	1536935	118
Sing Tao		Classroom	1997		1402	142201	101			
Chan Centre		Classroom	1997		8007	1161965	145	8007	38306	
Hennings		Laboratory	1945		11633	1231891	106	11633	828023	71
Leonard S Klink		Laboratory	1947		11264	6402108	568	11264	431156	38
Hebb		Laboratory	1964		6684	326832	49	6684	747443	112

					Electricity Metered Data			Steam Metered Data		
Building Name	LEED Equiv?	Category	Year of Cons-truction	Year of Renovation	Metered Area (m2)	Annual Consumption (kWh)	Elec BEPI (kWh/m2)	Metered Area (m2)	Annual Consumption (kWh)	Steam BEPI (kWh/m2)
EOSC Main		Laboratory	1971		14878	3298993	222	10613	1603426	151
CEME		Laboratory	1976		10327	960950	93	10327	1366333	132
Food, Nutrition & Health		Laboratory	1982		5939	1216330	205	5939	941108	158
CICSR/CS		Laboratory	1993		17544	3477379	198	10204	3650234	358
Chemistry Centre	Y	Laboratory	1925	2008	7399	3439802	465	7399	1466277	198
CHBE	Y	Laboratory	2005		14468	3080021	213	14468	4020550	278
HR Macmillan		Laboratory	1967		14619	1696025	116	14619	4303622	294
Forest Sciences		Laboratory	1998		22718	4763413	210	22718	7398913	326
Chemistry North		Laboratory	1962	2006	2753	1547777	562	2753	790390	287
Chemistry South		Laboratory	1959		5395	918999	170	5395	2537027	470
Chemistry Physics		Laboratory	1989		8740	3824477	438	7927	5369331	677
Beatty Biodiversity	Y	Laboratory	2009							
Kaiser	Y	Laboratory	2005							
Wesbrook Building		Laboratory	1949		9968	1395963	140			
ICICS	Y	Laboratory	2005		11604	2146109	185	10066	688436	68
David Strangway - Core	Y	Laboratory	2005		12200	3237671	265			
Life Sciences Centre	Y	Laboratory	2004		53916	20518191	381	53916	15890364	295
Michael Smith	Y	Laboratory	2004		8546	4954983	580			
Biological Sciences (Centre)		Laboratory	1948					10155	1842528	181
Biological sciences north wing		Laboratory	1976	2013				5334	2467646	463
Robert F Osborne Centre - Unit 2		Laboratory	1972		8539	608355	71			
Frederic Wood Theatre		Laboratory	1963		1989	160726	81			
Macleod		Laboratory	1963		7340	741358	101	7340	950390	129
Douglas Kenny		Laboratory	1983		14869	1645479	111			
Chemistry East		Laboratory	1963		3546	415204	117	3546	1238969	349
Frank Forward		Laboratory	1968		8411	994012	118	8125	146448	18
Pulp and Paper Centre		Laboratory	1985		3773	466962	124	3773	791810	210
Medical Sciences Block C		Laboratory	1961		4036	526352	130	4036	978551	242
Coal and Mineral Processing		Laboratory	1981		2681	355572	133	2681	228596	85
USB		Laboratory	1992		16575	2423406	146	9227	1957258	212
CEME Laboratory		Laboratory	1971		4599	775408	169	4296	608707	142
JB Macdonald		Laboratory	1967		7212	1367739	190	7212	2163450	300
SUB		Laboratory	1968		19394	4133942	213	19394	2728189	141
Biological Sciences West Wing		Laboratory	1970	2011	24560	6578891	268	9071	2550047	281
DH Copp		Laboratory	1961	2014	3926	1156255	295			
George Cunningham		Laboratory	1960		4996	1566676	314	4996	1624638	325
Brimacombe		Laboratory	1995		8551	2750743	322	8551	2900309	339

					Electricity Metered Data			Steam Metered Data		
Building Name	**LEED Equiv?**	**Category**	**Year of Cons-truction**	**Year of Renovation**	**Metered Area (m2)**	**Annual Consumption (kWh)**	**Elec BEPI (kWh/m2)**	**Metered Area (m2)**	**Annual Consumption (kWh)**	**Steam BEPI (kWh/m2)**
Biomedical Research Centre		Laboratory	1987		4312	1905227	442	4312	410081	95
I.K. Barber Learning Centre	Y	Library	1927	2007	25997	3759631	145	25997	2073280	80
Woodward Biomedical Library		Library	1964		7714	1029128	133			
Sedgewick Library		Library	1972		17587	2352431	134	17587	1685082	96
Asian Centre		Library	1975		4982	683425	137	7618	790383	104
Library Processing Centre		Library	1979		8458	1488352	176			
Henry Angus		Office	1965		13414	2116903	158	11964	964434	81
Frederic Lasserre		Office	1962		4709	375765	80	4709	629118	134
Music		Office	1967		7063	622625	88			
Liu Centre	Y	Office	2000		2940	194028	66	1760	184254	105
Friedman	Y	Office	1961	2008	1963	553670	282	4372	415909	95
CK Choi	Y	Office	1996		2724	158384	58	2724	301330	111
Auditorium - Annex B		Office	1969		5348	300063	56			
Buchanan Tower		Office	1972		10292	670184	65	10292	751896	73
Brock Hall Annex		Office	1956		2428	289230	119			
First Nations Longhouse		Office	1993		2158	261697	121	2158	380809	177
Thea Koerner House		Office	1961		4044	503762	125	4044	639701	158
University Centre		Office	1958		3978	498081	125			
GSAB		Office	1969		5829	898474	154	5829	879173	151
Brock Hall - East Wing		Office	1993		7699	1230435	160	7699	1174388	153
University Centre		Office	1958					3978	642214	161
Green College - all (not connecting to bldg 415)		Residence	1994		5685	317108	56	5685	1081432	190
Walter H. Gage Residence - all		Residence	1972		47927	2920429	61	47927	5516770	115
Marine Drive Towers		Residence	2006		62361	4175846	67			
Totem Park Residence - Haida/Salish, Dene/Nootka, Kwakiutl/Shuswap		Residence	1964		33345	2236680	67	29089	3271260	112
Totem Park Residence - Coquihala Common Block/Magda's Store		Residence	1964		33345	2236680	67	4255	740298	174
Place Vanier Residence		Residence	1961		36566	2865908	78	26761	5192634	194

Source: UBC University sustainability initiative BEPI database (2011)

Table C-2 The evolution of ASHRAE energy benchmark improvements since 1975.

ASHRAE 90.1	Year		MNECB		ASHRAE 189.1	
90 75	1975	100%	1997	92%	2009	48%
90A - 1980	1980	100%	2011	69%		
90.1 - 1989	1989	86%				
90.1 - 1999	1999	83%				
90.1 - 2004	2004	73%				
90.1 - 2007	2007	69%				
90.1 - 2010	2010	51%				
90.1 - 2013	2013	36%				

Source: (Halverson 2010).

Table C-3 Accumulated service areas 1915-2010.

	Accumulated Service Areas (m^2)			
	Class	Laboratory	Library	Office
1915	0	0	0	183
1920	0	0	0	1142
1925	0	310	0	1312
1930	3159	6440	0	9846
1935	3159	6440	0	9846
1940	4732	6861	9830	14138
1945	4732	7207	9830	14218
1950	5793	11357	9830	17260
1955	7765	18951	10054	25757
1960	7839	19027	10054	27284
1965	15828	25339	10054	35808
1970	21587	43557	15236	51729
1975	25286	59053	15808	69333
1980	28664	73638	24231	87905
1985	32638	84670	24231	102764
1990	33349	90796	24231	106896
1995	33349	97552	24231	109591
2000	34172	106191	27101	124505
2005	36013	112726	30111	130096
2010	43721	150780	30111	149521

Source: UBC Records (2012).

C.2 Variation in operational data

Energy consumption for all buildings is shown for a single year (2009-2010) and is plotted in Figure C-1 with respect to year of construction. For brevity, steam data is not shown, however similar variance is observable. Variability is evident for both pre- and post-2000 building types, especially for laboratories.

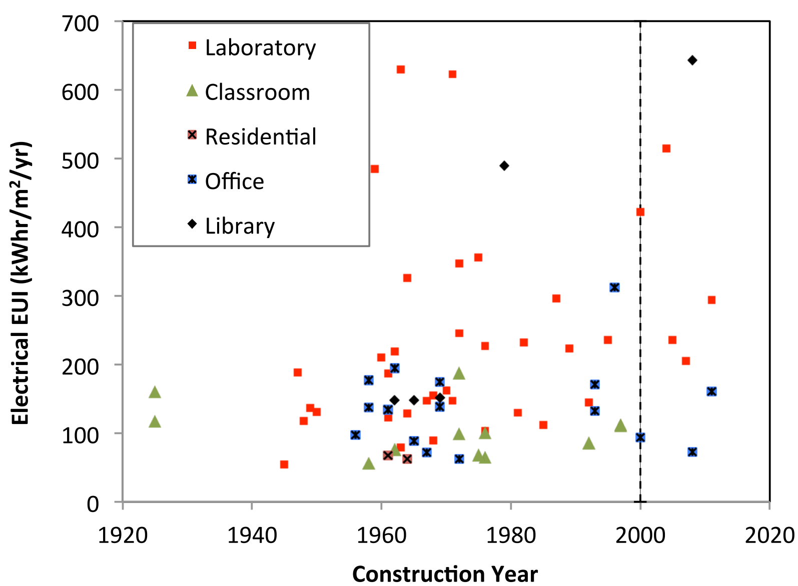

Figure C-1: Site operational electrical EUI for UBC-V buildings from metered data. Thermal values (steam) are suppressed for clarity. Linear trends lines through the data are omitted due to low R2 correlation values.

C.3 Ranking performance: LEED versus conventional buildings

Figure C-2 shows the distribution of electrical energy consumption in buildings ordered in ascending rank. The LEED buildings are seen to be scattered throughout the rankings. A similar scatter distribution for thermal energy services was found (data not shown).
An optimal outcome is that LEED, or at least newer, buildings should be clustered at the low end of each rank set, however, this is not evident in the data.

Of further interest in the rank plot is a small group of highly energy intensive buildings for each building type (except residences). These buildings are unusually poor performers and should be high priorities for energy upgrades. Note that upgrades to these select buildings will improve the mean group performance, but not necessarily the median performance.

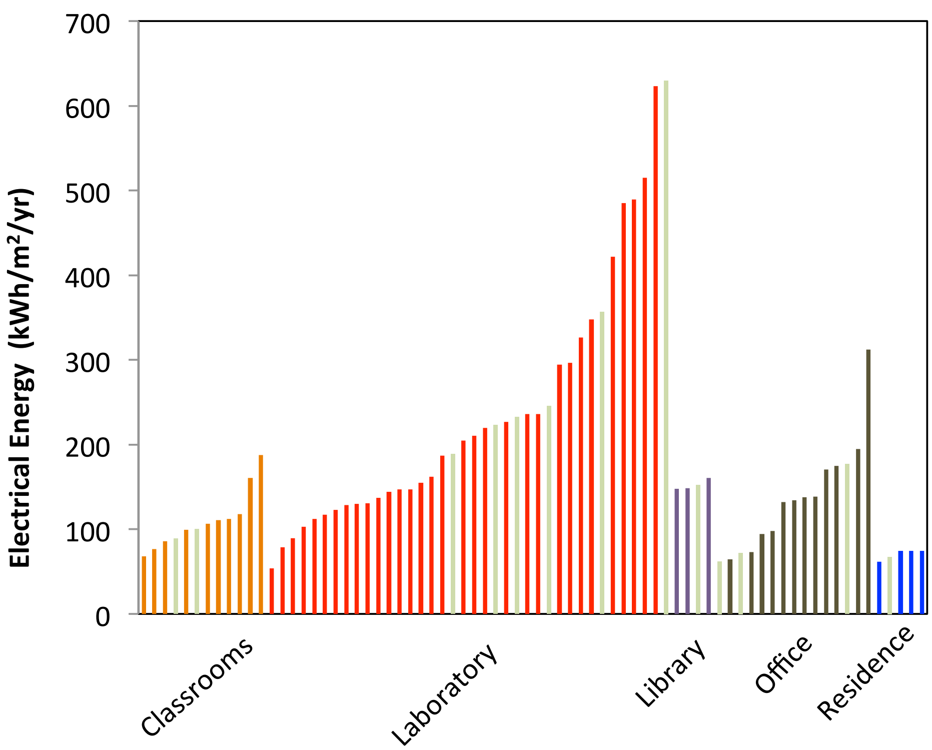

Figure C-2: Electrical site energy usage for 55 core buildings.
LEED 'equivalent' buildings are marked in green.