Life Cycle Assessment of Academic Buildings at UBC

CIVL 498C Stage 3 Final Project
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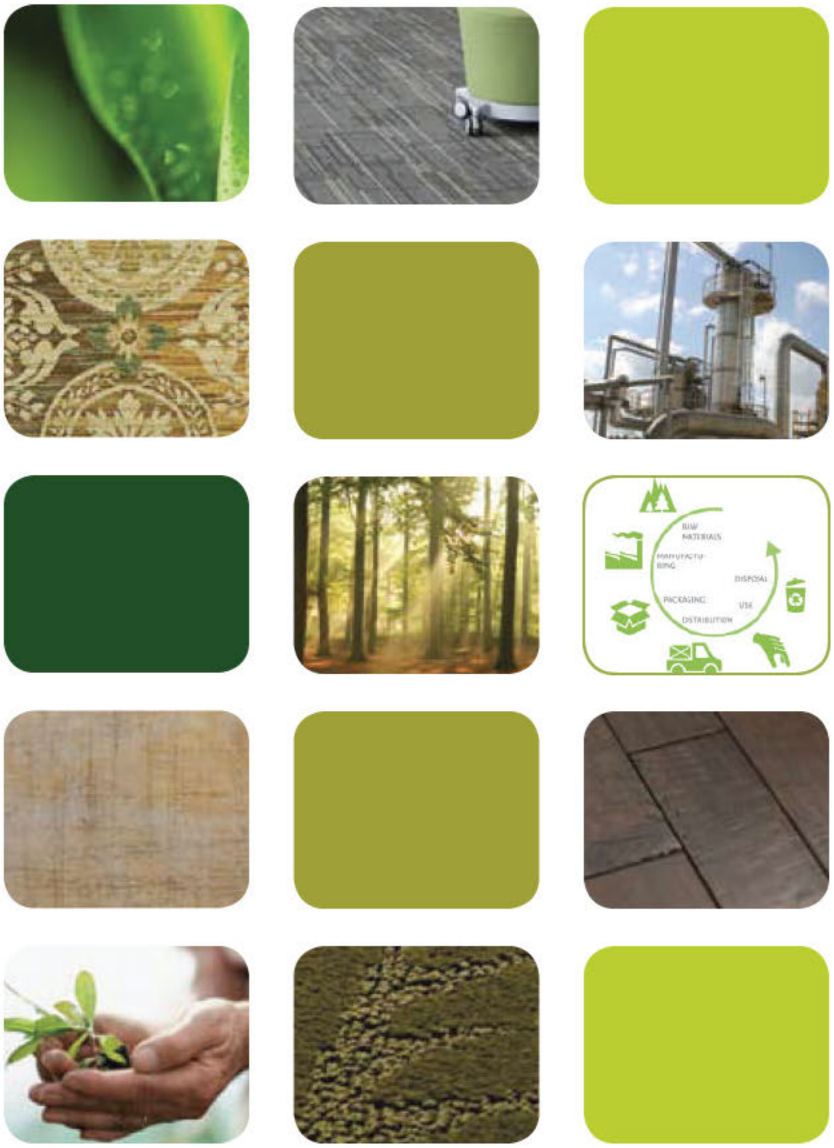
> “The only way forward, if we are going to improve the quality of the environment, is to get involved.”
>
> Richard Rogers



Executive Summary

This report is the final project in CIVL 498C, a course that introduces students to the practice of Life Cycle Assessment. It is part of a continuing study of buildings on campus, with the purpose of improving UBC's environmental footprint.

This study was based on a life cycle assessment of various buildings on campus done by students in the same course last year. Their results were updated and used as a benchmark for this project. The scope of this project is to gain more information about UBC's buildings, so that strategic decisions about new projects can be made in the future. The results can also be used as an educational tool for people to learn more about the environmental impacts of buildings on campus.

Some of the most noteworthy findings in the life cycle assessment are:

- Concrete constitutes about 81% of all construction materials in terms of mass.
- The 'Upper Floor Construction' of all the buildings is the largest building element assessed, with a total of 38% of all the construction materials.
- 'Roof Construction' was found to have the most significant environmental impact.
- The 'Product Stage' (manufacturing, transportation, material extraction) is the life cycle stage with the biggest impact

Comparisons were made between buildings in terms of "impact per square meter". A number of environmental impacts were considered, such as global warming potential, ozone depletion potential, non-renewable energy use, and fossil fuel consumption. A cost analysis was also made, which can help designers make decisions between choosing construction materials.

Some strategies to institutionalize life cycle assessment at UBC were also outlined. There are a number of ways to educate people about the concept, such as events, guest lectures, a newsletter, or through social media. Designers of buildings on campus can use modelling tools and a life cycle inventory database to make the process easier. With strong communication and education, life cycle assessment can be institutionalized into UBC policy to move towards a green future.

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1 Introduction

Life Cycle Assessment (LCA) is emerging as an important tool for designing green buildings. A number of design guidelines for UBC were examined, and it was found that UBC can use LCA to fulfill the requirements. LCA can be used to meet UBC's requirements for building LEED Gold status buildings.

A post-mortem Life Cycle Assessment (LCA) study was carried out on more than 20 academic buildings at the UBC Vancouver Campus. The goal of the study is to provide a transparent educational as well as a strategic planning tool used for current and future building constructions at the University of British Columbia. All the LCA models of previous CIVL 498C students were modified using the Athena Impact Estimator. A unified database, called CIVL 498C 2014 Database, was created in order to provide access to all the building impact assessment results. Also, a comprehensive description of the goal and scope for the study was developed in accordance with ISO 14044:2006 to assure transparency and completeness. Life cycle inventory (LCI) analysis and life cycle impact assessment (LCIA) analysis of all the buildings were evaluated, which allowed us to identify the hotspots within UBC building structures and determine which materials contributed the most to the buildings' environmental impacts.

Institutionalizing LCA at UBC may seem like a daunting task, but it can be achieved through a number of ways. People can be introduced to LCA through social media, events, or a newsletter, intended to open people's mind about the concept. Those interested in using LCA can take courses or workshops to learn more. LCA modelling tools and databases can make the process easier. Over time, LCA could be used on more and more projects at UBC, until it is entrenched as a required part of design and construction on campus.

2 Context for Use of LCA at UBC

The concept of Life Cycle Assessment has been developed over a number of years, and it is becoming more and more relevant to UBC. The following section summarizes several guidelines and action plans, and explains how LCA can support sustainability programs within construction and design at UBC.

2.1 UBC Climate Action Plan

The UBC Climate Action Plan (CAP) identifies the key action areas in which campus development and infrastructure is on the top of the list (University of British Columbia, 2010). One of the major components included in campus development and infrastructure is determining whether buildings are residential or institutional. Actions for Campus Development and Infrastructure are compiled into five key activity areas. Leveraging experience in development and emissions reduction for academic and research purposes (DV-05) is one of the activity areas where LCA can be applied. According to the UBC's CAP, an action to encourage sustainable procurement is working with UBC researchers to conduct life cycle analysis (LCA) on common purchases in an effort to define the embodied energy within the supply chain and to show buyers at UBC the life cycle cost of their choices. Although the above statement seems to be more about day-to-day purchases, a similar analysis could be performed regarding UBC's building design and operation. It is interesting that UBC's Climate Action Plan identifies LCA as an approach or tool to establish baseline inventory for the UBC food system, but it fails to do so for building design and operation.

The UBC's CAP is implemented using a management system framework facilitating the continuous improvement of a plan. The process consists of an ongoing feedback loop known as the Deming Cycle with the following four components: *Plan, Do, Check,* and *Act.* The nature of LCA falls within the described system, since LCA is a tool continuously assessing the environmental impacts of projects. On technical report #2 of the Climate Action Plan, the inventory documents GHG emissions associated with the buildings operations (i.e. GHG by utility energy source); however, it does not consider the GHG emission from building construction and materials.

2.2 The UBC RFI Evaluation Criteria

The UBC RFI Evaluation Criteria is a *request for information* documents informing contractors and bidders on how their response to the RFI is evaluated by the owner (i.e. UBC). UBC has assigned an innovative, holistic, integrated methodology and a work plan with a total 100 points, of which 5 points are awarded to life cycle assessment of project options and their costs (University of British Columbia, 2013). In addition, UBC requires an effective and a multi-disciplined team that is expected to have experience in an LCA of project options (5 points). However, the document is not clear whether the achievement of these points is mandatory or not. It seems reasonable that responses to the RFI will be marked out of 100, and the highest mark will be awarded the contract. Therefore, a respondent who lacks expertise in LCA could achieve points from other departments and still be awarded the project.

2.3 The UBC LEED Implementation Guide

The UBC LEED Implementation Guide provides specific direction for the UBC Vancouver Campus to implement the LEED Canada Building Design and Construction 2009 Rating Systems. It has been developed to support all UBC policy and it is aligned with the *UBC Vancouver Campus Plan.* The *LEED Canada BD+C 2009 Reference Guide* is still the core document. This document "identifies mandatory credits that must be achieved for UBC projects along with specific guidance for both mandatory and optional credits, where applicable. It acts as an application guide where further UBC specific direction is offered and UBC performance priorities are described. It is imperative to note that direction is only given where applicable to the UBC context; all other cases are to follow the Reference Guide." (University of British Columbia, 2013).

According to the guide, there are a total of 100 points available, of which 60 points are mandatory. Also, in order to obtain LEED Gold or LEED Platinum certification, you need 50-70 points and 80+ points respectively. The credits fall into various categories, from *Sustainable Sites* to *Regional Priority*. *Innovation and Design Process* is one of the elements under the *Innovation in Design* category that is assigned a total of 5 credits, of which all are mandatory (University of British Columbia, 2013). There have been numerous strategies that have earned ID credits under the *LEED CANADA-NC 1.0* rating system at UBC. Life Cycle Assessment is one of the many strategies that could potentially achieve the 5 mandatory points. Therefore, one does not have to necessarily use LCA, no matter how beneficial, to achieve the mandatory credits. In order for LCA to become institutionalized, UBC should incorporate LCA into the guide as a standalone element (still under *Innovation in Design* category) worth of 1-2 mandatory credit(s), and reduce the value of *Innovation and Design Process* accordingly.

2.4 Metrics of Sustainable Buildings

The article *Metrics of Sustainable Buildings* argues the following points (Ospelt, n.d.):

- Tools supporting green and sustainable design need to be simpler, more transparent and credible in order to be better integrated in mainstream design.
- Every LCA tool faces a trade-off between scientific accuracy and objectivity on one hand and high aggregation for a simpler and effective level of communication to a wider audience on the other hand.
- LCA does not cover social equity and local economics.
- Many tools sees to neglect the fact that the scientific background for some of these impact categories are still very weak, for example global warming
- Two ways to bring LCA results into design process:
    - 1) Aggregate by valuation into one index which adds another source of error and subjectivity
    - 2) Concentrate only on the most important issues
- Greenhouse gases and global warming are considered to be the most important factors/impacts

- Toxicity is the 2nd most important impact, as it covers the widest range of effects on humans and nature.
- Resource consumption is another impact that is totally different from the other impacts. That being said, its evaluation and characterization is in its early stages of development.
- LCA and the database are very new. Therefore, its impacts and indicators should be reviewed regularly.
- "A few impacts represent the biggest overall impact of buildings. For example, building construction only is a minor contributor to Eutrophication compared to overall loads"; thus it can be neglected.
- Lack of inventory data is the reason why little info based on LCA has been used in the design process.
- In Europe, the government is a supporter of LCA and the database is public, rather than being private.
- If the LCA database is based on the average of several companies, disclosure of secret production data of a company can be prevented. Therefore, even more companies will be motivated to get involved and cooperate.

2.5 Life Cycle Impact Assessment Weights to Support Environmentally Preferable Purchasing in the United States

The article *Life Cycle Impact Assessment Weights to Support Environmentally Preferable Purchasing in the United States* argues that although LCA is a quantitative method for understanding the environmental impacts of a product, all product purchasing decisions are still subjective. Thus, weights need to be introduced to link or transform the quantitative results of LCA to the value-based subjective choices or decision makers. For example, BEES, an LCA tool synthesizes the performance scores for all impact categories into a single score in order to compare the overall environmental performance of competing products. This is done through weighting, a value-based process that represents the scientific interpretation and ideological, political, and ethical principles. The motivation for employing weighting is based on the desire to simplify LCIA output, especially in circumstances where trade-offs across a product system occur. There are critics of LCA who argue that LCA should be an objective environmental evaluation procedure.

In order to develop this set of weights, NIST solicited input from a volunteer stakeholder panel. This paper presents the weight results from this stakeholder panel employing the Analytic Hierarchy Process (AHP) as described by *ASTM Standard E 1765-2*.
It is a systematic approach to finding the priorities of a range of decision criteria and then measuring the contribution of potential solutions to those criteria. In the context of BEES, the AHP is used to develop a set of importance weights for environmental impacts so that life cycle impact assessment results may be synthesized to measure overall environmental performance for alternative building products.

One criticism raised against the AHP concerns the requirement to explicitly state and incorporate subjective judgments. This requirement is rejected by some members of the operations research and management science communities, who are reluctant to adopt a method that does not claim to be purely “objective.”

The AHP is well suited to facilitate interpretation of LCIA results. It does so by arranging and comparing decision criteria in such a way that decision makers can logically and consistently evaluate all of the criteria in a complex decision problem. Their low weights may indicate lack of immediate concern or that the remedial actions associated with the impact, for the most part, are underway. (Gloria, 2007)

2.6 Vancouver Campus Plan Design Guidelines

The life cycle analysis of buildings at UBC is relevant to the Campus Design Guidelines provided. The guidelines state that “all projects must be designed to integrate sustainable best practices in design” (University of British Columbia, 2010), which goes hand in hand with the reasons for carrying out an LCA. An LCA will help designers make sustainable choices when choosing construction materials, such as sourcing materials locally or choosing long-lasting materials.

An LCA can also establish comparative assertions to achieve the stated goal of ensuring “the quality and stature of a globally significant University” (University of British Columbia, 2010). Benchmarks can be set against other prestigious universities to showcase UBC’s dedication to the environment. More detail about benchmarking and comparative assertions is in the LCA Decision Making Methods section of the report.

UBC also aims for “economic sustainability through use of design and material selection strategies” (University of British Columbia, 2010), and LCA can be used to get quantifiable economic information about materials in order to make informed decisions. An LCA can help determine which materials will be most cost effective, by comparing values such as availability, transportation, maintenance requirements, and component service life.

LCA also provides quantifiable impact results in order to procure “products that maximize lifecycle and can be reused or recycled” (University of British Columbia, 2010). Recycling on campus is widespread, so as part of the cradle-to-grave assessment, recyclable materials can be incorporated into the building, to be recycled at the end of the service life.

2.7 LEED v4

Undergoing an LCA of the buildings on campus can help fulfill the objectives outlined in LEED v4. Points can be awarded for “achieving a minimum level of energy efficiency for the building and its systems” (LEED, n.d.), which ties closely to the analysis in the life cycle inventory phase. LEED outlines requirements to “reduce construction and demolition waste disposed of in landfills and incineration facilities” (LEED, n.d.), and an LCA can be used to meet them. Points can also be awarded for choosing products with environmental product declarations which “have at least a cradle to gate scope” (LEED, n.d.). In summary, a life cycle assessment is a useful tool to complete the LEED requirements.

2.8 Performance Objectives

The following objectives are established by UBC Technical Guidelines, which are mandatory requirements for UBC. Some of these requirements are as follows:

- It is important for all projects to comply with their performance targets and meet their sustainable design objectives such as reducing energy consumption and greenhouse gas emissions.
- Projects at UBC need to be designed in a way to achieve the minimum life cycle cost of ownership. The materials and equipment must be taken into account as well.
- Building components, finishes and systems should be designed with the minimum maintenance requirement throughout its life cycle.

UBC is a “learning community” (UBC Building Operations, 2014) and as a community it needs a comfortable, creative, and uplifting environment.

2.9 Energy Efficient Buildings Strategy: More Action, Less Energy

Life Cycle Assessment (LCA) determines the environmental impact of products, starting from the raw materials to ending with its recycling. LCA can be used to get LEED points in order to have a more sustainable environment. The construction industry is a large contributor to carbon dioxide (CO2) emissions. This report covers what the government of British Columbia is doing to provide tools into the hands of residents to make new and better choices. Their goal is to reduce greenhouse emissions by 33% by 2020 and they are doing everything in their power to achieve this goal. The BC Energy Plan has a vision to minimize the environmental impact by using clean energy sources, meeting minimum requirements for Gold LEED points, upgrading and using new equipment in homes, etc. There was no mention of LCA in this article, even though the focus of the article is to have a more sustainable environment. The focus of energy efficiency is on the operation phase of the building through the lifecycle of the building and using better sources of energy. LCA can help look at aspects such as materials, heating, cooling and ventilation systems, which can optimize the building’s environmental performance and impact over its entire life cycle. The use of LCA can help and encourage designers and architects to use LCA studies in the design phase of new projects. This way, energy consumption and its impacts can be calculated and benchmarked in every stage of the building life cycle. For example, depending on the systems used in buildings or homes, LCA studies can show the phases with the most impact.

UBC has been exploring all aspects of sustainability in terms of economic, environmental and social impacts. UBC has been investing in energy management and through several projects over the past few years; they have reduced the energy consumption and greenhouse gas emissions throughout the campus, and have saved a significant amount of money. With this plan they are also touching base on Life Cycle Cost assessment and how a great amount of money can be saved through efficient use of energy on campus.

2.10 Learning Space Design Guidelines

This report outlines the design guidelines for formal and informal learning spaces in UBC. It outlines in detail, the process of designing spaces such as planning, designing, furnishing, lighting, sustainability principles, functional programming, the review and approval phase and every other category that is required in order to design, renew or renovate a project.

Use of LCA in the Technical Guidelines of UBC can help architects and designers to have baseline quantitative and qualitative data when designing new spaces. By comparing the entire building and different elements of the building, architects and designers can measure the environmental impacts and show the results to the owners and shareholders. The results indicate that certain materials or a certain design will cause global warming, smog formation, or human health issues. Through the goal and scope phase of LCA, all the project participants and committee members can analyze the project outline and the purpose of the project. In the inventory analysis, using all the inputs and outputs of each element, the potential environmental impact can be discussed and measured. With the use of LCA in the Technical Guidelines, we can define what materials, models and methods have the least impact.

3 LCA Study of Academic Buildings at UBC Vancouver Campus

In accordance with the ISO 14040 and 14044 standards, this report will describe the Goal and Scope, summarize the Inventory Analysis and Impact Assessment Results, provide findings, and give concluding remarks.

The following Goal and Scope section outlines the details of the LCA study that was carried out on more than 20 existing academic buildings at UBC Vancouver Campus. All of the details of this study are explicitly outlined in the Goal & Scope section below. The buildings considered in this LCA study are listed in the Model Development section of this report.

3.1 Goal & Scope

The first and most critical step in conducting an LCA study is to unambiguously define the goals and scope of the analysis (Johnson, 2006). The purpose of defining the Goal is to clearly state the intended purpose and application of the study, whereas the purpose of defining the Scope is to point out how the actual modeling of the study was carried out (Athena Institute, 2011). In order to clearly outline the details of parameters outlined in ISO 14040 and 14044:2006, the following format has been used or this LCA study report to describe the essential elements of goal and scope definition.

The Goal & Scope followed a similar format to that of Biosciences LCA Study, prepared by Athena Institute in 2011. An explanation of each parameter is provided, and there is a statement on how they are defined for the LCA Study of Academic Buildings at UBC Vancouver Campus.

3.1.1 Goal of Study

The following are descriptions for a set of parameters which unambiguously state the context of this LCA study.

Intended application

Describes the purpose of the LCA study.

This LCA study will be used within a regional context in the following ways:

- as a strategic planning and educational tool for current and future building projects via establishing a benchmark against the currently existing UBC buildings. For example, it could give UBC insight on various strategies for construction of the most energy- and cost-efficient buildings.
- as a policy making tool for UBC on how to approach the institution of LCA in building design and operations.
- as an educational and archetypal demonstration tool showing the latest developments in environmental impact accounting methods in order to help encourage and improve education on LCA and further its development in building construction and operation practices at UBC and the green building industry in general.

Intended audience

Describes those who the LCA study is intended to be interpreted by.

The results of this LCA study are to be primarily communicated to the UBC Green Building Management, UBC LCA researchers, and the general public. With LCA being an emerging topic of significance in the field of green building, other intended audiences of this LCA report could be but are not limited to industry and government groups observing and involved in this field.

Intended for comparative assertions

State whether the results of this LCA study are to be compared with the results of other LCA studies.

The results of this LCA study are intended for internal comparative assertions as part of a benchmark database for UBC LCA Database. However, this study has not been prepared for external comparative assertions, such as comparing the buildings to other institutions and schools.

3.1.2 Scope of Study

The following are descriptions for a set of parameters that detail how the actual modeling of the study was carried out.

Product system to be studied

Describes the collection of unit processes that will be included in the study.

“A unit process is a measurable activity that consumes inputs and emits outputs as a result of providing a product or service” (Athena Institute, 2011). The main processes of the product system being studied in this LCA study are 1) the manufacturing of construction products, 2) the construction of the buildings, 3) the utilization of buildings, and 4) the demolition of buildings. These four processes are the building blocks of the LCA models that have been developed to illustrate the impacts associated with the academic buildings being studied in this LCA report. The unit processes and inputs and outputs considered within these four main processes are similar to that of the BioSciences LCA study done by Athena Institute in 2011 provided in Annex C.

It is notable that the unit processes of manufacturing the construction products, construction of the buildings, and utilization of the buildings capture the cradle-to-gate, whereas the building demolition unit process captures the grave. Here, cradle to gate refers to resource extraction, manufacturing construction products, and construction of buildings, while grave simply refers to the end of life for a product system (Athena Institute, 2011). In order to further define the product system being examined in this LCA study, one must define the system boundary.

System boundary

Details the extent of the product system to be studied in terms of product components, life cycle stages, and unit processes.

This LCA study examines the construction products used to create the structures and envelopes of the academic buildings being studied at UBC Vancouver campus. Therefore, the product components must be defined by the materials within the studied products (Athena Institute, 2011).

> The material product components (i.e. building assemblies) that were included from the products (i.e. buildings) are the footings, slabs on grade, walls, columns and beams, roofs, as well as all associated doors and windows, gypsum board, vapour barriers, insulation, cladding and roofing. These material product components are in turn assemblies of construction products. (Athena Institute, 2011)

The following figure demonstrates the life stages included within the system boundary from the product stage all the way to the end of life stage. The modules included within the analysis scope of this study are shown in blue.

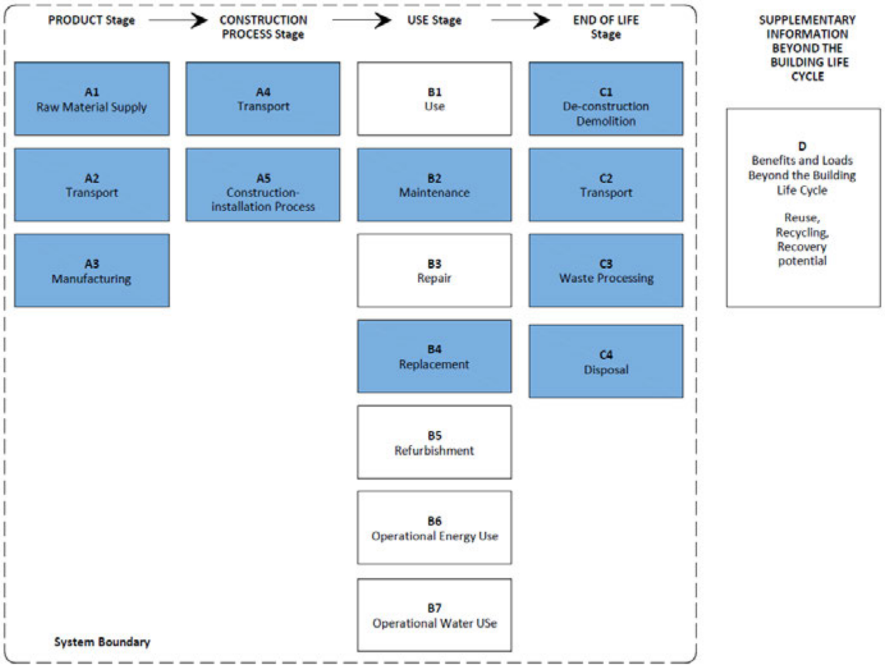

Figure 1: Building LCA System Boundary According to EN 15978 (analysis scope shown blue)

As seen from the figure, the whole system studied here represents a cradle-to-grave scenario or process. The process begins with cradle-to-gate life cycle phase capturing the resource extraction, manufacturing of construction products, building construction, and maintenance and replacement. Then, it ends with grave life cycle phase which captures the demolition of the buildings and the transportation and disposal of demolition wastes (Athena Institute, 2011).

Functions of the product system

Describes the functions served by the product focused on in the LCA study.

Each of the buildings modeled in this LCA study are designed to serve mainly as an academic institutional building on the UBC Vancouver campus. They also serve "as safe and climate controlled buildings separating their occupants and structure from the environment" (Athena Institute, 2011).

Functional unit

A performance characteristic of the product system being studied that will be used as a reference unit to normalize the results of the study.

The functional units used as a reference to normalize the results of this LCA study are ***per square meter post-secondary academic building constructed***. The functional units are used as a reference to draw comparison between academic buildings serving the same function yet differing in square meter (i.e. area). Alternatively, the functional unit of *per post-secondary academic building constructed* can be used to compare buildings of similar function and square footage. That being said, this LCA study only includes the *per square meter post-secondary academic building constructed.*

Allocation procedures

Describes how the input and output flows of the studied product system (and unit processes within it) are distributed between it and other related product systems.

The three allocation scenarios to be aware of are 1) a process outputting multiple products, 2) a waste treatment process having multiple inputs, and 3) an open loop recycling. The open loop recycling scenario is identified as when material are recycled or reused in subsequent life cycle stages (Athena Institute, 2011). It comprises of various procedures such as cut-off, relative loss of quality, 50/50 rule, and closed loop approximation.

Referring to Figure 1, it is evident that this LCA study follows an *open loop recycling* allocation scenario. Since the LCA in this study does not include the processes where raw materials are created and where demolished materials are treated (i.e. they are out of system boundary), it can be implied that the cut of allocation[1] was the procedure used in this scenario.

Impact categories selected and methodology of impact assessment

State the methodology used to characterize the LCI results and the impact categories that will address the environmental and other issues of concern.

This LCA study reports only on the impacts that meet the objectives of this study and are relevant to the intended audience of applications of the study. The following is the list of considered midpoint impact

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[1] According to Athena Institute, the cut-off allocation method entails only the impacts directly cause by a product within a given life cycle stage are allocated to that product (Athena Institute, 2011).

categories and their respective units used to express them (i.e. category indicators). Each impact category if further explained in Annex B.

- Global Warming Potential - kg CO_2 equivalent
- Acidification Potential - kg SO_2 equivalent
- HH Particulate - kg $PM_{2.5}$ equivalent
- Eutrophication Potential - kg N equivalent
- Ozone Depletion Potential - kg CFC^{-11} equivalent
- Smog Potential - kg O_3 equivalent
- Total Primary Energy - MJ
- Non-Renewable Energy - MJ
- Fossil Fuel Consumption – MJ

Depending on which impact categories considered, methodologies may vary. The primary methodology of impact assessment used for this LCA study has been the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) which is developed by the United States Environmental Protection Agency (US EPA). Athena Impact Estimator, developed by Athena Institute, was also used as the modeling tool required to explore the environmental impact or footprint of the product system studied. The interpretation and analysis of the results associated with the above impact categories are included in the Results and Discussion sections of this report.

Data requirements

Explicit statement of measured, calculated or estimated data needed to inform your modeling of unit processes.

Two main types of data are used for developing LCA models. 1) Primary Data collected directly from the specific process being modeled and 2) Secondary Data for general processes reported by someone else (Sianchuk R. , 2014). In this case, secondary data was the main type of data used for developing the LCA study.

This LCA study was developed based on the following main sources of data: 1) Building assemblies 2) Data contained within the Impact Estimator (i.e. Athena LCI Database). All the measured, calculated, and estimated data for the building assemblies were developed by previous students of CIVL 498C via performing material take offs on architectural and structural drawings. This information was provided to us in order to reproduce Bill of Materials for the buildings studied in this assessment.
The other source of data used in this study was the Athena Life Cycle Inventory (LCI) Database developed by Athena Institute and embedded in the Impact Estimator software. Although the Database is not publicly available, most of the reports and information that developed the database are available on the Athena Institute webpage [www.athenasmi.org] (Athena Institute, 2011).

Data quality requirements

Quantitative and qualitative characterization of quality of modeling and data used in the study including its time related, geographical and technological coverage, precision, completeness, representativeness, consistency, reproducibility and uncertainty of the information.

The quality of modeling methods and data used in this LCA study can be addressed based on the sources of data: building assemblies and the LCI database.

The measurements, calculations, and estimates of the building assemblies were obtained by previous students of CIVL 498C. All the data collected were from the original architectural and structural drawings of the academic buildings on UBC Vancouver campus and were to be documented in a specific format to assure completeness. All the material take offs were derived by Quantity Take-Off software to improve consistency and precision. As for the reliability of the database, two buildings (Pharmaceutical Sciences Building and School of Music) were found to be lacking in completeness and precision; hence, excluded from the database.

The quality assessment of the data and modeling assumptions associated with the LCI database was beyond the scope this study due to proprietary nature of the Athena LCI Database. That being said, there are several sources of uncertainties typically associated with LCA studies and LCI databases. The main types of uncertainties include data, model, temporal and spatial variability, and variability between sources. For example, some of the buildings (i.e. Math and Geography Buildings) in this LCA study were constructed in the 1920s, yet the LCI database being used is based on data available in 2014 which leads to misrepresenting the impacts of the original buildings. Further explanation and examples are provided in Annex D.

Assumptions

Explicit statement of all assumptions used to by the modeller to measure, calculate or estimate information in order to complete the study of the product system.

The assumptions used in this LCA study are associated with the main sources of data identified earlier (i.e. building assemblies and Athena LCI Database).

A service life of 60 was assumed for LCA modeling of all the buildings. Other than that, all assumptions regarding measurement, calculation, and estimation of the building assemblies were made by previous students of CIVL 498C and can be found in the appendix of each building's LCA report from last year. Assumptions associated with the LCI database "have all been developed by Athena Institute and are built in to the Impact Estimator [version 5.0.01]. This information is proprietary; however, parts can be accessed through the inner workings report found on the Athena Institute webpage" (Athena Institute, 2011).[2]

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[2] The Inner Working of the Impact Estimator for Buildings: Transparency Document - http://www.athenasmi.org/tools/impactEstimator/innerWorkings.html

Limitations

Describe the extents to which the results of the modeling carried out on the product system accurately estimate the impacts created by the product system defined by the system boundary of the study.

The limitations to interpreting the result of this study are mainly associated with system boundary and data and modeling assumption.

Impacts created from recycling and reuse of materials from construction or demolition were outside the system boundary for this study.

This LCA study is based on the building assemblies measured, calculated, and estimated by last year's students. The information on the building assemblies were developed by obtaining material take offs on the original architectural and structural drawings. Therefore, "the resulting LCA models are specific to these buildings as their bills of materials reflect their unique designs" (Athena Institute, 2011).

There are some modelling assumptions that are inherent when using the Impact Estimator software. Product manufacturing and fuel refining data is based on North American averages. The transportation matrix that estimates modes and distances of product transportation and waste is specific to Vancouver, BC. Also, the LCI data in the IE software was developed to reflect current circumstances and technology.

Type of critical review

A review of the methods, data, interpretations, transparency, and consistency of the LCA study.

This LCA study has not been prepared for a critical review, but care was taken to ensure that the LCA process has been fully transparent.

Type and format of the report required for the study

Statement of the type and format followed by the report.

This report is provided in accordance with ISO 14044 and follows the final report outline provided by the supervisor of this project, Rob Sianchuk.

4 LCA Model and Study Development

This section provides discussion on the development of the LCA model and study summarized in this report. This LCA study was carried out in three stages over the course of the term. The first stage was focused on updating the academic buildings in the UBC LCA Database, whereas the second stage was focused on benchmarking and assigning LEED points to the buildings in study. The last stage was to report on the current use of LCA at UBC and the updated UBC LCA Database, and to provide suggestions on the future of LCA at UBC.

4.1 Stage 1

In the first stage, each student was assigned an academic building from the UBC Vancouver campus and provided all the files and documents associated with that building. All the files and documents provided were developed by the CIVL 498C students of previous year (2013). Each student were to update the Athena Impact Estimator (i.e. *.AT4) files of each building by modifying the *Building Life Expectancy* to 60 years and produce a Bill of Materials and a detailed Summary Report of the building's environmental impacts. The results of each building were then to be uploaded in a single document available to all students of CIVL 498C in order to update the UBC LCA database[3].

4.2 Stage 2

In the second stage, each student was to create a benchmark of all building impact assessment results (i.e. the results from detailed Summary Reports) and total material mass by square meter (I.e. the results from Bill of Materials) for whole building and each respective element[4]. Only the impact assessment results associated with the life stages within the system boundary were considered (i.e. A to C)[5]. Each student compared their own building design to the whole building class benchmark previously calculated and to comment if any LEED MR point can be awarded. This stage allowed us to study the accuracy of the building's LCA model and to see whether any building's results were off compared to the baseline[6].

4.3 Stage 3

Stage 3, combined with the other two Stages, make up the CIVL 498C final project. In this stage, each group of three students were to provide a final report on the context for use of LCA at UBC, the academic buildings at UBC Vancouver campus, and strategies for institutionalizing LCA at UBC. The CIVL 498C 2014 LCA database was further optimized in order to eliminate any inconsistency in the results.

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[3] The updated UBC LCA database is referred to as CIVL 498C 2014 LCA database throughout this report.

[4] Refer to 2013 CIVL 498C Level 3 Elemental Construction Format in Annex E for more information on the building elements considered in this study.

[5] Refer to System Boundary in Goal and Scope section for more information.

[6] Baseline was calculated as the average of all the buildings' impact assessment results.

4.4 CIVL 498C 2014 Database

The CIVL 498C 2014 database initially included the Impact Assessment results and the Bill of Materials associated with 24 academic buildings at UBC Vancouver campus listed below. However, after further optimization and reliability assessment of the database, two buildings were excluded from the scope of study due to unreliable or missing critical information. The list of academic buildings included and excluded from the study is as follows.

Buildings Included in the Study			
Aquatic Ecosystems Research Laboratory	AERL	Geography	GEOG
Allard Hall	ALRD	Hebb	HEBB
Henry Angus	ANGU	Hennings	HENN
Civil and Mechanical Engineering	CEME	Institute for Computing, Information, and Cognitive Systems	ICICS
Chemical and Biological Engineering	CHBE	Fred Kaiser	KAIS
Chemistry	CHEM	Douglas Kenny	KENN
Chemistry North Wing	CHEMN	Frederic Lasserre	LASR
Chemistry South Wing	CHEMS	Mathematics	MATH
Centre for Interactive Research on Sustainability	CIRS	Macmillan	MCML
Earth Sciences Building	ESB	Neville Scarfe	SCRF
Forest Science Centre	FSC	Wesbrook	WSBK
Buildings Excluded from the Study			
School of Music	MUSC	It was excluded due to missing information regarding area quantities and Bill of Materials.	
Pharmacy	PHRM	It was excluded due to unreliable impact assessment results.	

Table 1: List of Buildings Included in the Study

5 Results and Interpretation

This section summarizes the environmental impacts and materials used in academic building designs at UBC. It also provides discussion on what the results demonstrate about designing buildings that minimize environmental impacts and on rules of thumb for the design of elements by assembly type and material selection. Following these discussions are some recommendations for future efforts in institutionalizing LCA at UBC.

5.1 Inventory Analysis

In the Life Cycle Inventory (LCI) analysis, an inventory of flows to and from the product system in question is created. To develop the inventory, “flow model of the technical system is constructed using data on inputs and outputs. The input and output data needed for the construction of the model are collected. Then, the environmental loads of the system are calculated and related to the functional unit, and the flow model is finished” (Athena Institute, 2011). The input data for this study was obtained by previous students from each building’s structural and architectural drawings. These inputs were then fed into the Athena Impact Estimator to create a Bill of Materials.

Bill of Materials (BoM)

The Bill of Materials generated for each building includes a list of all the materials with their amount used in the construction of the building. For consistency, the amount of materials used for all the buildings is provided in *Tonnes*. It should be noted that Bill of Materials output from Impact Estimator also takes account into material waste from construction of the buildings.[7]

The table in Annex K illustrates the total Bill of Material results of the whole building for all UBC Academic Buildings studied. The total Bill of Material results of each building element for all UBC Academic Buildings are also presented in Annex F.

The Bill of Material results for the whole building (Annex K) and each element (Annex F) have been categorized into different material categories in order to make identification of construction materials easier. The *Material Categorization Index* used for this purpose is included in Annex G. The followings are the summary of the results for all the elements including the whole building.

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[7] Athena Impact Estimator calculates construction wastes by assigning a *Construction Waste Factor* to each specific construction material (e.g. 1 m^3 of Concrete 30 MPa (Flyash av.) with 0.05 *Construction Waste Factor* is equivalent to 1.05 m^3)

Material Category	Unit	Whole Building	%
Wood	Tonnes	1,508.65	0.53%
Wall Coverings	Tonnes	3,186.66	1.12%
Metal	Tonnes	9,909.93	3.47%
Roof Materials	Tonnes	5,910.16	2.07%
Masonry/Bricks	Tonnes	31,250.53	10.95%
Concrete	Tonnes	231,826.60	81.24%
Insulation	Tonnes	284.75	0.10%
Glass	Tonnes	1,444.47	0.51%
Plastics	Tonnes	15.97	0.01%
Miscellaneous	Tonnes	26.37	0.01%
Total	**Tonnes**	**285,364.10**	**100%**

Table 2: Categorized Total Bill of Materials of All UBC Academic Buildings

As seen from the above table, concrete makes up about 81%[8] of the total material used in construction of all UBC Academic Buildings[9]. Masonry, with 11% and Metal, with 3.5% are respectively the second and third most used construction materials. The fourth and fifth most used material in construction of all the buildings are roof materials, with 2.1% and wall coverings, with 1.1%. The rest of the materials identified are relatively insignificant as each makes up less than 1% of the total.

The following table contains the total Bill of Material results of all UBC Academic Buildings[9] for each element (i.e. A11, A21… B11). Refer to Annex F for a description of each element.

Material Category	Unit	A11	A21	A22	A23	A31	A32	B11
Wood	Tonnes	0.00	48.11	466.96	454.01	24.91	191.03	323.62
Wall Coverings	Tonnes	9.01	30.38	100.92	159.65	168.33	705.33	2,013.05
Metal	Tonnes	83.16	185.17	5,062.36	1,239.46	321.31	1,211.62	1,806.84
Roof Materials	Tonnes	0.00	0.00	435.82	4,337 56	0.14	1,134.99	1.65
Masonry/Bricks	Tonnes	0.00	0.00	217.52	8.79	871.47	11,870.94	18,281.80
Concrete	Tonnes	38,397.12	15,330 57	102,840.93	21,515.80	14,638.93	22,101 28	17,001 97
Insulation	Tonnes	0.01	0.00	21.18	98.13	16.93	89.81	58.68
Glass	Tonnes	0.00	0.00	0.00	29.75	67.60	1,132.47	214.65
Plastics	Tonnes	0.87	3.05	0.00	4.17	1.99	5.42	0.47
Miscellaneous	Tonnes	0.00	1.47	1.44	4.10	0.39	7.26	11.71
Total	**Tonnes**	**38,490.17**	**15,598.76**	**109,147.15**	**27,851.43**	**16,112.00**	**38,450.15**	**39,714.44**

Table 3: Categorized Total Bill of Materials for Each Element

A11 Foundations

Concrete is the primary source of material in this element as it makes up about 99.8% of the total materials used which is reasonable due to the nature of the element. There are other materials used such as metals, wall coverings, and plastic; however, they make up less than 15% of the total.

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[8] It should be noted that these numbers represent the sum of materials used in construction of all the buildings studied and does not represent a mean or average value for these buildings.

[9] Refers to all the academic buildings at UBC Vancouver campus that are included in the study (as previously discussed)

A21 Lowest Floor Construction

Similarly, concrete, with 98% is found to be the primary source of material used for this element. About 186 tonnes of metal were used for the lower floor construction of all the academic buildings, which amounts to about 1% of the total materials used. Wood, wall coverings, plastics, and paint materials are among other materials used for this element.

A22 Upper Floor Construction

Concrete, with 94%, is once again considered to be the most construction material used for this element. It is notable that amount of concrete used in the construction of the upper floor of all the academic buildings makes up about **44%** of the total concrete and **36%** of the total materials used in the construction of all UBC Academic Buildings. This amount could potentially be one of the reasons for a high GHG impact associated with this element. Metal is the second most material used with 5% and the remaining 1% is made up of wood, roof materials, masonry, wall coverings, and insulation and miscellaneous materials. The amount of metal used in this element makes up **51%** of the total metal used for the construction of all the buildings.

A23 Roof Construction

Although concrete is the most material used for roof construction, it is not as significant as in the previous elements. In roof construction, concrete makes up 77% and roofing materials make up about 16% of the total materials used for this element. The roof material used in A23 accounts for almost **73%** of all roof materials used for construction of all the buildings. As seen from the table, every type of material identified under *Material Category* is used in roof construction of all the buildings.

A31 Walls Below Grade

As expected from the nature of this element, concrete is found to be the most material used making up 91% of the total materials used in the construction of all the walls below grade for all the buildings. Masonry and metal are the next most used materials each accounting for 5% and 2% of the total materials for this element. The use of glass material seems to have increased from previous elements although not enough to make up for more than a percent of the total materials.

A32 Walls Above Grade

In construction of this element, the amounts of concrete and masonry materials account for 57% and 31% respectively. The amount of masonry used in this element also accounts for **38%** of the total masonry used in all the buildings. Metal, roof materials, and wall coverings combined made up 8% of the total materials used in this element. The amount of glass used had considerably increased (i.e. relative to previous elements) accounting for 3% of the total materials in A32 and **78%** of the total glass materials used for all the buildings.

B11 Partitions

Masonry or brick is found to be the most material used in the construction of this element for all the buildings. It accounts for 46% of the construction materials used in this element and about **59%** of all the masonry materials used for construction of the buildings. The remaining major materials used are concrete, wall coverings, and metal respectively making up 43%, 5%, and 5% of the total materials used in constructions of this element for all the buildings. The table below contains the total material mass used for construction of each element for all the buildings.

Element	Unit	Total Material Mass	%
A11	Tonnes	38,490.17	13%
A21	Tonnes	15,598.76	5%
A22	Tonnes	109,147.15	38%
A23	Tonnes	27,851.43	10%
A31	Tonnes	16,112.00	6%
A32	Tonnes	38,450.15	13%
B11	Tonnes	39,714.44	14%
Whole Building	**Tonnes**	**285,364.10**	**100%**

Table 4: Total Material Mass of Each Element

The results from above table show a staggering amount (i.e. 38%) of materials being used for upper floor level construction of all the buildings.

5.2 Impact Assessment

Inventory Analysis is by Life Cycle Impact Assessment (LCIA) in which the LCI outputs are characterized based on their potential environmental impact. Refer to Annex B for a description of the impact categories included in this study.

The impact assessment phase aims to evaluate the potential environmental impacts based on the LCI results. Next, the inventory parameters are sorted and assigned to impact categories in the classification stage. Characterization involves the conversion of the LCI results to common units, and the converted results are aggregated in the same impact category (Athena Institute, 2011). The factors used in the process are called 'characterization factors'.

This LCA study was prepared with Athena IE, using TRACI as the database. The buildings were assessed from cradle-to-grave, where there impacts are considered from the manufacturing to the end of service life. However, recycling of building materials after demolition and earth work during construction was not considered. Equivalent units were set to compare the impacts in each category.

The life cycle impact assessment (LCIA) results from the LCA models of all UBC Academic Buildings are presented in the following tables and figures. The results presented are in terms of Level 3 elements (i.e. A11, A21…B11) and life cycle stages. The following table illustrates the sum and average of Total Impacts per m^2 of total constructed area[10] for all the buildings. Refer to Annex I for more information on total constructed area of each element as well as whole building.

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[10] Total constructed area for the whole building is calculated as the sum of ground floor and upper floor areas (see Annex I)

Impact Category	Units	Total	Baseline
Global Warming Potential	kg CO2 eq	8.72E+03	3.96E+02
Acidification Potential	kg SO2 eq	5.72E+01	2.60E+00
HH Particulate	kg PM2.5 eq	2.70E+01	1.23E+00
Eutrophication Potential	kg N eq	6.65E+00	3.02E-01
Ozone Depletion Potential	kg CFC-11 eq	4.10E-05	1.86E-06
Smog Potential	kg O3 eq	1.19E+03	5.42E+01
Total Primary Energy	MJ	1.49E+05	6.77E+03
Non-Renewable Energy	MJ	1.41E+05	6.43E+03
Fossil Fuel Consumption	MJ	8.67E+04	3.94E+03

Table 5: Summary of Environmental Impacts of all UBC Academic Buildings (Total Impact / m^2)

The average of Total Impact per m^2 of all the buildings were calculated to generate a baseline for future benchmarking purposes. Similar results have been generated for all Level 3 elements presented in Annex H. The following figure summarizes the impact assessment results of level 3 elements for all UBC Academic Buildings. It is generated from the *Mean of Total Impacts per m^2* table in Annex H.

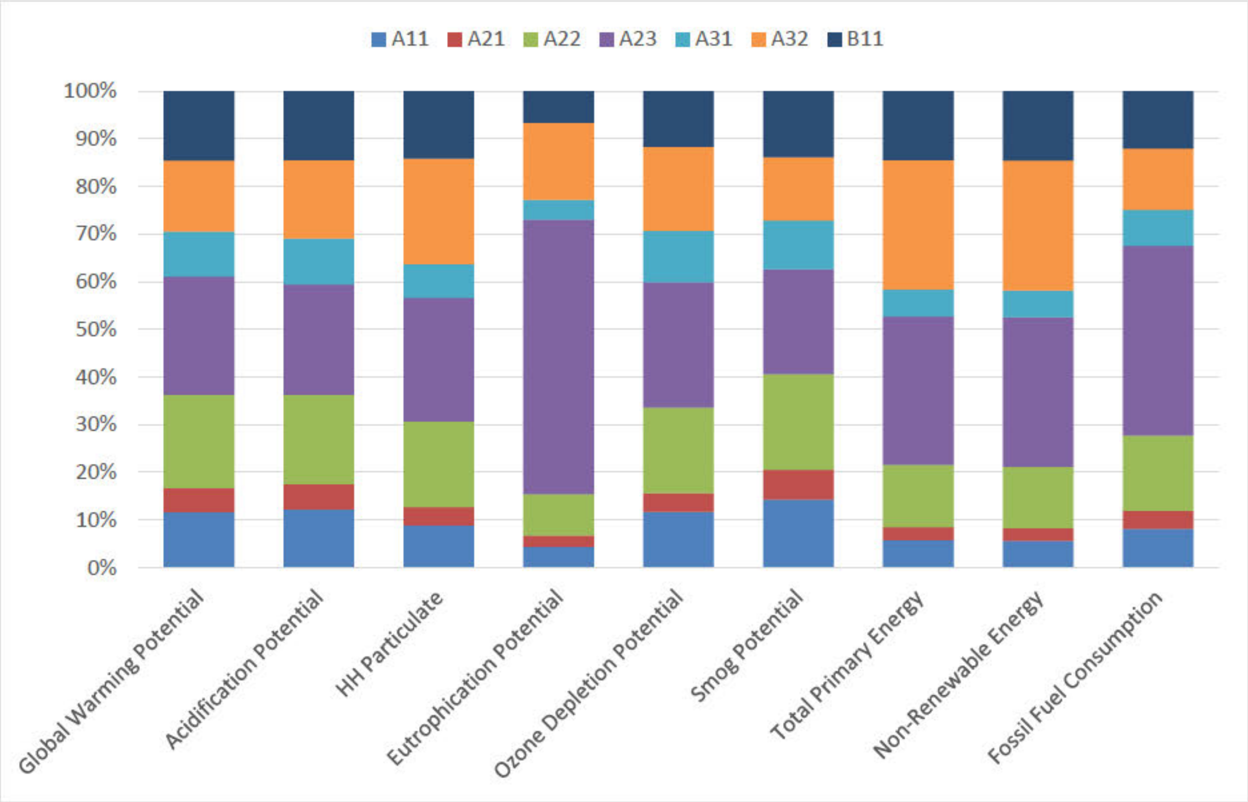

Figure 2: Level 3 CIQS Element Hotspots

The figure above gives a general idea as to where hotspots are within the UBC Academic Building structures. It is evident that *A23 Roof Construction, A32 Walls Above Grade*, and *A22 Upper Floor Construction* are the primary contributors in the UBC Academic Buildings' environmental performance. All three of these elements have concrete materials as their primary source of material. Looking at each element separately:

A23 has a significant amount of roof materials which makes up about 73% of all the roof materials used for all the buildings. Roof materials are sub-categorized into organic felt, ballast, EPDM membrane, bitumen membrane, polyethylene filter fabric, roofing asphalt, PVC membrane, and type III glass felt. Roof materials are a major contributor of eutrophication and acidification which justifies the high percent impact of A23. Also, roofing materials such as gravel tend to be heavy thus requiring a lot of energy for transportation. A32 contains 78% of the total glass materials and A22 has 44% of total concrete and 51% of total metal materials used for the construction of all the buildings. These materials could potentially be the origin for all the high impacts across different categories.

The following figure illustrates LCIA results by life stages within system boundary. Product stage seems to be the most impactful among all impact categories except eutrophication potential in which use stage is the dominant contributor. Construction process is a significant contributor to only smog and acidification potentials. End of life stage is consistently a minor contributor among all impact categories except smog potential. As seen from the results, product stage is found to be the hotspot and the main area of focus for improving the LICA results.

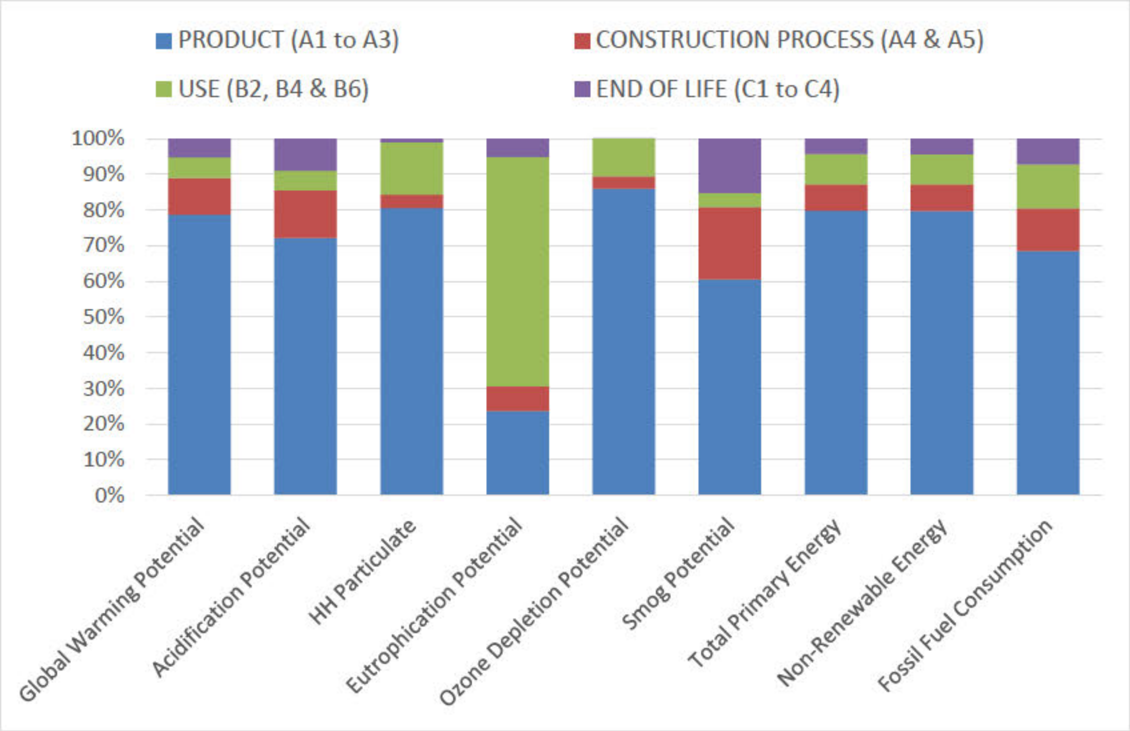

Figure 3: Life Cycle Stage Hotspots

The following series of figures illustrate the same results based on process modules in order to further investigate the impact associated with each stage. The results seem to be only consistent for the end of life stage. Transportation plays a minor role in this stage; thus more attention should be given to greener strategies for demolishing buildings, and disposal and waste processing of construction materials.

The inconsistencies for the first three life stage results seem to be from transportation of materials. Smog, being air pollution, is generally the result of air emissions from vehicles and industries. Therefore, the distance between the location of extraction and manufacturer or manufacturer and the construction sites could be the reason for such a high impact contribution percentage. This also explains why transportation plays a major role in the construction process stage's total impact.

Overall, manufacturing is the primary concern for improving LCA of construction materials. Hence, many organizations have been seeking after LCA certification in construction material. Recently, the US Green Building Council officially declared ingraining LEED v.4 with MRc1 and MRc2 - 2 LCA based credits in Materials and Resources (Athena Institute, 2013). This is possibly the start up for LCA to become a necessary fixture with which manufacturers could gain transparent sustainability credits (Russell, 2013).

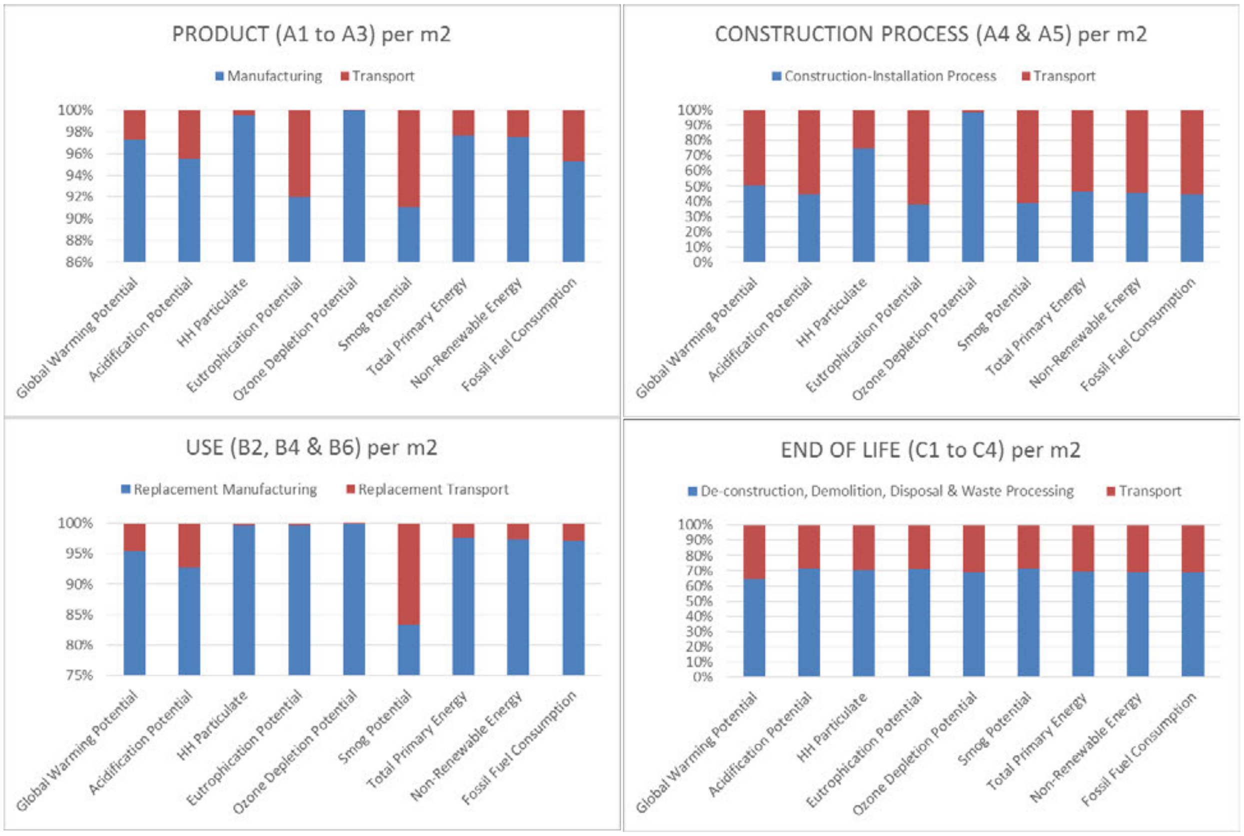

Figure 4: Process Module Hotspots for Each Life Cycle Stage

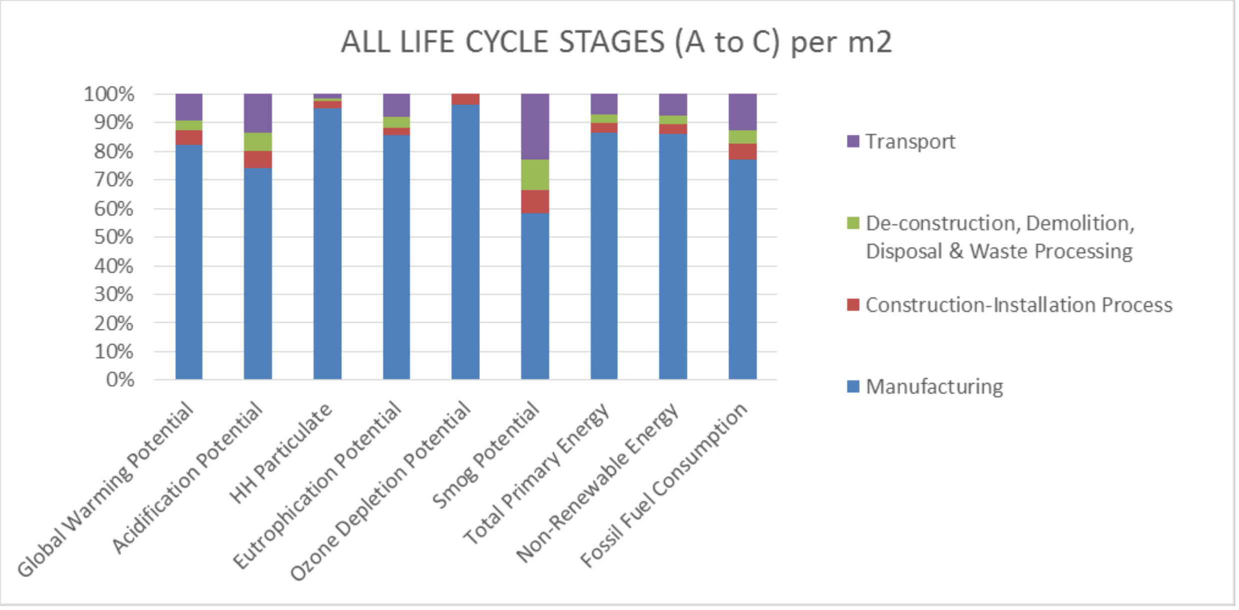

Figure 5: Process Module Hotspots for All Life Cycle Stages

5.3 UBC Academic Benchmark

This section provides the results of benchmarking UBC Academic Buildings against a baseline created, similar to Stage 2 of the CIVL 498C final project. The Pharmacy Building and School of Music were excluded from the benchmarking due to missing or erroneous results. A baseline was calculated by averaging the results for all the buildings. It should be noted that the Douglas Kenny building did not have any walls below grade construction. Therefore, KENN was excluded from averaging the results associated with A31 Walls Below Grade. The results are summarized in a series of tables included in Annex H.

Figure 10 in Annex J benchmarks the overall performance of all UBC Academic Buildings against the baseline and alongside each other. The results indicate that buildings such as HEBB, ALRD, CEME, and LASR which were built more than 30 years ago (i.e. in 1960s-1970s) have the lowest overall impact. Looking at the buildings constructed in that last 10 years (i.e. CIRS, AERL, KAIS, & CHBE), it is notable that CIRS, a LEED Platinum certified building, has the lowest overall impact in most of the categories. Hence, it is not surprising that “CIRS was designed to be a best practice project” (UBC Sustianability , n.d.).

Figure 6 illustrates a scatter plot of global warming potential and total costs of the UBC Academic Buildings. The CIVL 498C 2014 database was missing construction cost data for some of the buildings (GEOG, HENN, and SCRF), thus they were excluded from this section of the study. The construction costs are 2013 costs calculated by previous students and available in CIVL 498C 2014 database.

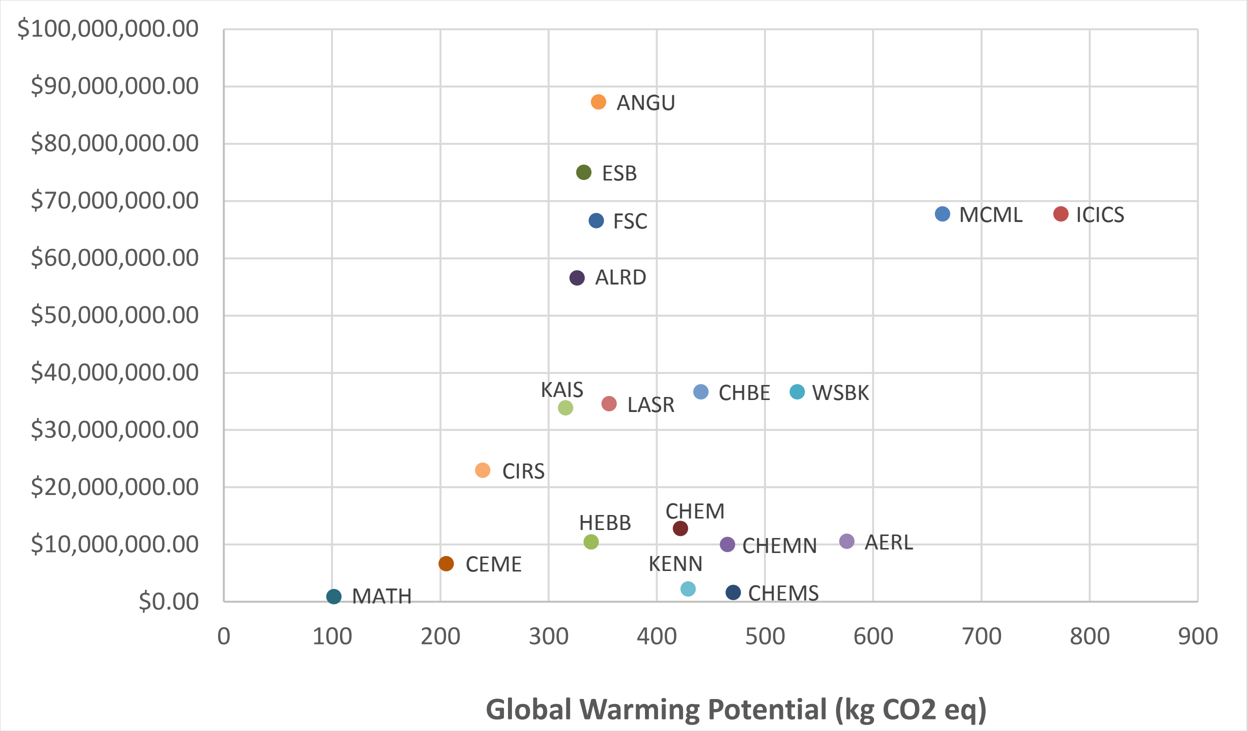

Figure 6: UBC Buildings Global Warming Potential vs. Construction Cost (2013 $)

Starting from the lower-left corner of the plot, Math and Civil and Mechanical Engineering buildings seem to be performing very well relative to others. As moving to the higher-right corner of the plot, the GWP and construction costs both increase, indicating a relatively poor performance. MacMillan and ICICS are found to be the two worst performing buildings. CIRS building, which is considered to be a best practice among other buildings, demonstrates a relatively well performance against the others.

From the benchmarking results, it is implied that older buildings are generally performing better than the average. There are, however, limitations to reliability of these results. The Math building - built in the 1920s - is a prime example here. Back in the 1920s the construction costs were relatively cheaper and the use of more natural materials was more widespread than today.

5.4 Sensitivity Analysis

A sensitivity analysis is mainly used to evaluate the sensitivity of results to an independent variable. In this case, a sensitivity analysis is used as a tool to determine which material properties and assembly types impact the overall environmental impact of a building. In order to perform a sensitivity analysis on the buildings in this study, modifications to material properties and assemblies must be made through each building's .AT4 files (i.e. Impact Estimator output files). Since the files for most of the buildings were not accessible, our group relied on the results of a sensitivity analysis on selected construction materials used in Math building (Annex L).

The following modifications were made to material properties and assembly types in order to maintain the structural soundness of the building:

- Concrete 30 MPa (Flyash av) was changed to Concrete 30 MPa **(Flyash 35%)**
- Stud Spacing of Wood Joists were changed from 16" oc to **24" oc**
- Concrete 30 MPa (Flyash av) was changed to Concrete **60 MPa** (Flyash av)

The original impact assessment results of the building was considered as the baseline. Then the impact of each modification was individually evaluated against the baseline. The results of the analysis are detailed in a table in Annex L. The following figure summarizes the building life cycle impact variations as a result of each modification.

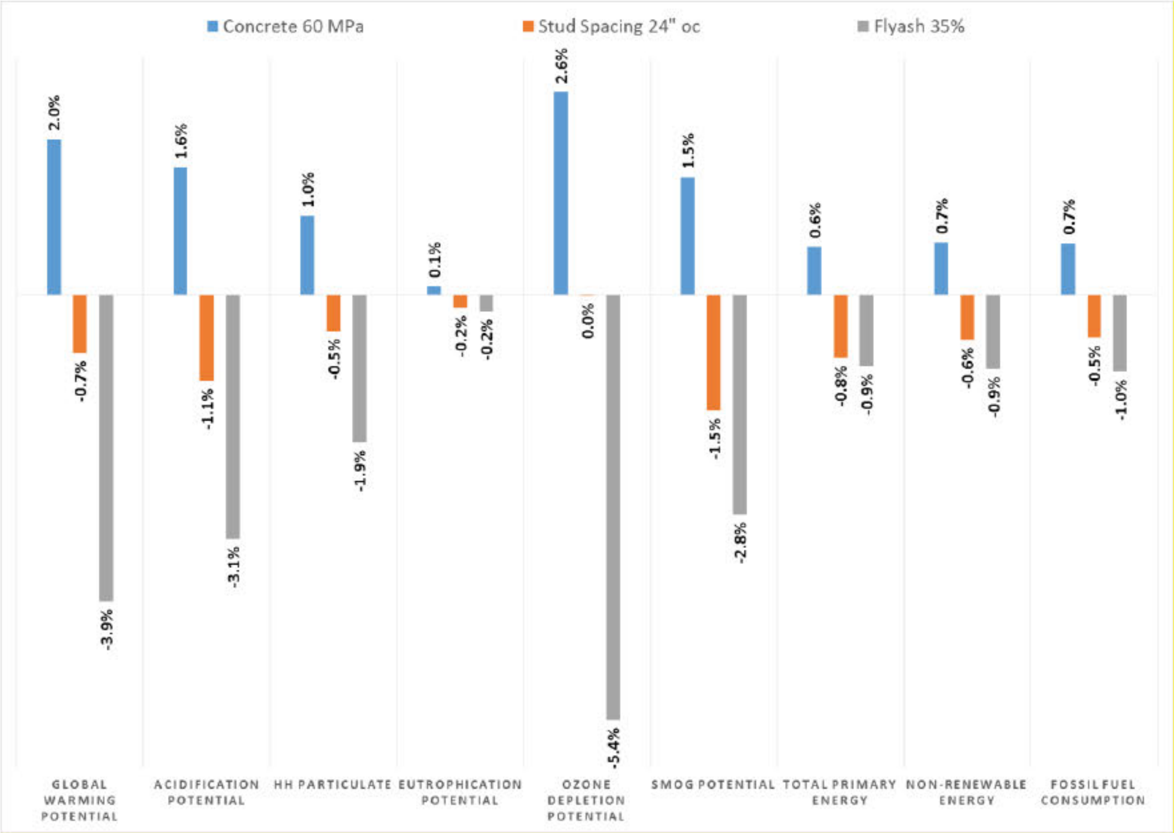

Figure 7: Building Life-Cycle Impact Difference

It is notable that flyash percentage had the most overall impact on the building's life cycle assessment results. Increasing the flyash to 35% resulted in building life-cycle impact reductions across all impact categories. Increasing the strength of the concrete to 60 MPa while maintaining an average percent flyash resulted in an overall increase in the life cycle assessment results of the building. Increasing the stud spacing of wood joist showed a similar behaviour to that of flyash as it also resulted in a building life cycle impact reduction. It is important to underline that Math building is among the smallest buildings at UBC which makes this a relatively small-scale sensitivity analysis. The results of a larger scale analysis might be much more drastic.

Such a sensitivity analysis is most beneficial when it is applied during the design phase as it allows designers to approach design alternatives more objectively. An example would be utilizing a comprehensive sensitivity analysis to evaluate the environmental impacts of constructing a new building versus renovating an existing one at UBC. Incorporating sensitivity analysis into the LCA study will certainly allow designers to develop proposed designs that can achieve LEED MR points. Next section further discusses the future of LCA at UBC and where or how this LCA study can be used.

6 Next Step for Institutionalizing LCA at UBC

To institutionalize a new topic, it is important to properly educate people and make them realize the importance of it. People are open to learning new topics if it interests them. Vancouver is already a highly sustainable city and many residents are introduced and educated on what green means to some extent. Therefore, introducing them to life cycle analysis will not be too challenging. But how can one tell something is truly "green"? And what is being done to achieve the goal of green? In order to make a difference in our world, we need to start making changes and alter the path we have been walking on. When people are motivated to find solutions to problems, they will do anything in their power to solve them.

6.1 LCA Modeling Tools

6.1.1 UBC Policy

There are different modeling tools within LCA, such as Athena Impact Estimator, Excel, Eco-Calculator, Tally, etc. One of the more well-known and accurate ones is the Athena Impact Estimator, which is offered in the CIVL 498C-Life Cycle Assessment course in the Engineering Department at UBC, and also available for staff and students. University of British Columbia has many technical guidelines and regulations that designers and architects need to meet when designing a new project at UBC such as the minimum Gold LEED requirement. Since 2008, all new and renovated buildings at UBC need to meet the minimum requirement of Gold LEED (University of British Columbia, 2013). Architects and designers are able to gain 5 LEED points if they do an LCA study, which currently optional (University of British Columbia, 2013). Therefore, one thing that can be done to grow LCA at UBC is to make LCA a mandatory deliverable. LCA could also become a mandatory requirement of the new projects at the campus.

When institutionalizing a “new phenomenon and a new idea into the business world, it has to be done often enough for it to become a routine use.” (Frankl, 2000). In order to institutionalize LCA studies at UBC, it is important for the policy makers and those in charge of the technical and design guidelines of UBC to incorporate LCA studies as a mandatory deliverable (top bottom effort). At UBC the integration of LCA studies started from the bottom up effort from graduate students and after a few years of continuous research, education and development, staff and faculty members are also joining the topic of LCA (top bottom effort) (Sianchuk, 2013).

6.1.2 Athena Impact Estimator and Tally

The Athena Impact Estimator is an LCA-based software that helps designers to incorporate environmental information into their design and study the impact of different materials. It gives “architects, engineers and analysts access to advance life cycle inventory data without requiring advanced skills.” (ASMI, 2014). Once given the accurate information like different materials, size and quantity, the Athena Impact Estimator measures and reports footprint data for the environmental impacts and calculates the bill of materials associated with those impacts. If doing the LCA studies is a mandatory deliverable of UBC, then companies designing and building new projects are obligated to learn LCA and LCA modeling such as the Athena Impact Estimator.

Another great idea is to introduce the Tally program into the Building Information Modeling (Civl 526-BIM) mandatory course offered to the graduate students at the Engineering Department of UBC. In that course, students are introduced to Revit and 4D modeling. Tally is a program that can easily be incorporated into that course since it is a Revit plug-in. Tally is an Autodesk Revit application that has the ability "to quantify the environmental impact of the building materials for the entire building analysis as well as comparative analysis of design options." (Autodesk, 2014). Tally demonstrates and measures the environmental impact of materials just by clicking on the material. Therefore students not only learn how to do a 4D modeling, but they also learn and get introduced to LCA and different impacts each material can have. This leads to better decision making when designing a project.

The LCA and BIM courses can also be offered as a mandatory course in the Architecture, Interior Design Departments and Landscaping Departments. This way, students graduate with the LCA knowledge and background, and companies designing new projects at UBC can take advantage of their knowledge.

6.2 LCA Databases

6.2.1 Mandatory Database

In today's society, leveraging from other business's knowledge is crucial. Leveraging can lead to a multiple management benefits such as, faster growth, faster innovation, quality improvement, saving in cost and resources, employee and customer satisfaction. Many companies have been using benchmarking to constantly improve their performance. The CIVL 498C-Life Cycle Assessment course has been offered for 7 years now and over these years, as part of the course deliverable, students have developed a database with all the necessary information taken from on-screen takeoff software, to measure the bill of materials and different environmental impacts of them. The database developed in CIVL498c includes the bill of materials and life cycle inventory assessment for most of the buildings on campus. This database could be a great benchmark for the future projects built at UBC.

As part of making the LCA study at UBC a mandatory regulation and guideline, as mentioned in the previous section, designers and architects would be updating this database once they have designed a new project. Then this database could become a reference point for the future projects and therefore every project that's being designed and built would be benchmarked against this database. Therefore every project would be better than the rest of the buildings built before. Designs and use of materials would improve after each building and this could be a path to a more sustainable environment with less environmental impacts.

6.2.2 Environmental Product Declarations

UBC will keep track of all EPDs used in construction projects and will make them available to use for everyone. "An Environmental Product Declaration, EPD®, is a verified document that reports environmental data of products based on life cycle assessment (LCA) and other relevant information and in accordance with the international standard ISO 14025" (Environdec, n.d.). The EPDs provide a quick method to involve LCA in the construction process. Over time as more EPDs are collected the LCA process will become faster and easier.

6.3 LCA Decision Making Material

6.3.1 Community

Certain considerations will be made to ensure that the decisions made in the LCA are in the best interests of the community. For example, Divest UBC is a new organization on campus that aims to "reduce exports of greenhouse gases" and advocates "UBC divestment from fossil fuel" (UBCC350, 2014). If the movement generates a large amount of support on campus, then their objectives may need to be considered in the LCA.

Every year, the Alma Mater Society holds elections which occasionally ask for student opinions about environmental issues at UBC. In 2014, students voted 76.9% in favour of UBC divesting from fossil fuels (Alma Mater Society, 2014). In the coming years, there may be more concern about specific environmental issues, and the AMS may hold referendums about them. The results of the referendums will be observed when weighting the criteria for the LCA.

6.3.2 Benchmarking

There are many things that an LCA at UBC could be benchmarked against. Buildings at UBC can have comparative assertions to others on campus, other buildings in Vancouver, or other campuses worldwide.

A benchmark could be set against older buildings on campus to demonstrate that UBC is moving towards a greener future. An LCA could produce quantifiable comparisons between construction materials used in elements of buildings. Over time, as more and more green buildings are built on campus, the standard will become higher and higher. This will ensure that campus is constantly becoming greener.

The city of Vancouver is aiming to be the greenest city in the world by 2020 (City of Vancouver, 2012), and undertaking an LCA on campus would help UBC contribute to the city's prestigious reputation. Buildings on campus could be benchmarked against the most environmentally friendly buildings in the city, to show that UBC's are as good or better. For example, the City of Vancouver National Works Yard is Vancouver's greenest building. It achieved LEED Gold status by using ground source heating, photovoltaic power, vegetated roofs, recycled construction waste, and use of local materials (Sustainable Solutions, 2009). The Vancouver Convention Centre hosts zero-waste events, uses water recovery systems, optimizes energy use, and has one of the largest living roofs in the continent (Vancouver Convention Centre, 2009). The Van Dusen Botanical Garden Visitor Centre is self-sustaining, through its use of rainwater collection, geothermal energy, and solar power (SAB Magazine, 2014).

These examples of green buildings in Vancouver are a very high standard to benchmark against. Buildings that succeed in comparison to the greenest buildings in Vancouver would be very significant and prestigious sites on campus.

UBC also aims to be a world-class university (University of British Columbia, 2010), so an LCA could be used to make comparative assertions against other campuses. The University of Northern British Columbia is regarded to be one of the greenest universities in Canada. It uses many windows to reduce the need for light, LED lights to reduce electricity, and has a highly sustainable bio-energy power plant (University of British Columbia, 2012). The University of Ottawa has a unique 5-storey living wall which provides air filtration to the Social Sciences building (University of Ottawa, 2012). York University uses recycled concrete, roads that incorporate storm water management, natural light, and low use of volatile organic compounds (York University, 2014). Setting a benchmark against these prestigious universities would help establish UBC as a world-class university.

6.3.3 Cost

Cost can have a considerable effect on the feasibility of constructing a green building. For example, community members or stakeholders may be advocating the use of a particular environmentally friendly material. Even though using that material may result in a green building, it may be unattainable due to cost. Material costs can arise due to availability or transportation, to the point that it is not cost-efficient. Maintenance requirements can also affect decisions in an LCA. Some materials may be environmentally friendly, but could need replacement in a short amount of time. Doing an LCA could help UBC make financial decisions when designing new buildings.

6.3.4 Weighting

The impacts of the buildings will be weighted according the desired benchmarks, costs, and input from the community. One approach to get feedback appropriately is to establish a stakeholder panel (Gloria, 2007). The panel generally consists of stakeholders, producers, users, and LCA Experts. Next, a number of environmental impacts are discussed, and a survey is taken to decide which ones are the most significant. A variety of statistical techniques such as hierarchy, relative weights, and consistency can help determine the final scores. However, the main limitation of this method is the subjective nature of the voters. Their opinions may differ greatly, and the results can be affected.

6.4 LCA Communication and Education Resources

6.4.1 Internal Uses

An LCA can be used internally to determine which buildings on campus are making the most impact on the environment, so that UBC can attain its sustainability goals. An LCA can be applied to determine “environmental critical points” (Frankl, 2000) in a product’s life cycle. Knowing the critical points can help designers on campus in making sound decisions. An LCA can also be applied to the construction of new buildings or renovations, so that they are environmentally friendly and cost effective.

In the long-term, an LCA can be used to make strategic decisions in cost analysis and material choices. A building may have a high up front cost, but an LCA can help ensure that it is designed to be long lasting. As mentioned earlier, an LCA can help make strategic cost decisions when choosing materials.

6.4.2 External Uses

The results of an LCA can be used externally to showcase UBC's dedication to the environment. As part of UBC's goal to be a world-class university, the LCA results could be published publicly, to show that UBC is truly a green campus. Publicly sharing the LCA could generate more interest in the topic at UBC. Sessions, lectures, or workshops could be held to discuss the results.

However, presenting the results can often be challenging because of the "complexity of the results" (Frankl, 2000). The results often show many numbers in a lot of categories, so it is important to present them in an organized manner. There are many assumptions such as system boundaries, service life, and energy use. There may also be uncertainties in the data or results that need to be addressed. If UBC publicly shares an LCA, it will need to show a lot of information but it will also need to be transparent about the assumptions and uncertainties.

6.4.3 Communication

An LCA database for UBC could be developed and regularly updated with new information. It could be presented publicly to let students know which buildings are most environmentally friendly, or it could be private and be used when designing new buildings.

UBC could put up a website, blog, or publication to document the progress of LCA on campus. It could be presented in a way that would be easy for people new to LCA to understand. A one-page document could sum up the most important findings for casual readers, and a detailed document can also be posted for those interested. Users could also sign up for a newsletter, which would be updated regularly with new LCA findings and keep people informed about sustainability events on campus.

In the last few years, social media has been one of the most dominant ways to reach people. For example, the UBC Sustainability Facebook page has over 1,000 people subscribed. The page regularly posts about news, issues, events, and developments on campus. A similar page about LCA could be established. It could help generate interest in a more 'fun' manner, by using easier learning techniques such as a simple "Did You Know?" page, filled with interesting facts about LCA at UBC. If an important accomplishment is made, it is easy for the news to spread through social media. For example, if a building at UBC succeeds in the benchmark against all other universities in Canada, then that accomplishment could be shared on the social media page and users will spread the news.

6.4.4 Education

Guest lecture events on campus could be used to educate students about LCA. The lectures would explain the benefits of LCA and the progress that UBC has made. Students could learn about ways to get involved with LCA on campus or in the workplace. For example, a professional engineer could present an introductory lecture about LCA, with a focus on the overall concept and the benefits it can provide to society.

Workshops could give students a hands-on approach to learning about LCA. It could take the format of a one-day accelerated education about LCA. The overall concepts would be taught, and the participants would have to use them to complete a task. The results would be compared with others at the end, and the instructor could provide feedback. The activity could involve an assessment for a new building on campus.

LCA could be integrated into a number of engineering departments at UBC. Civil engineering can include LCA in a wide variety of construction projects. Mining engineering students may benefit from LCA concepts in designing mines. Materials engineering could incorporate LCA concepts when creating long-lasting designs.

In the future, an organization similar to APEGBC could be established to focus on LCA in British Columbia. Currently, the Life Cycle Initiative is one of the biggest organizations devoted to LCA. Something similar could be established in the region. Engineers could learn about other projects in the region, and important knowledge about LCA can be exchanged.

An LCA certificate program could be established at UBC, just like the LEED certificate. It would be a strong part of a resume for graduating students. Companies could also start having a requirement for students with an LCA certificate.

6.4.5 Institutionalization Process

Institutionalizing LCA at UBC may be complicated and time-consuming, but it can be more feasible if it is approached in a few phases.

First, LCA could be implemented in a small area or on a specific construction project in the "habitualization stage" (Frankl, 2000). During this phase, the users can get familiar with LCA and learn how to use it effectively. A building like the new SUB would be a good example for this.

Next, LCA can be "semi-institutionalized" (Frankl, 2000). In this phase, LCA would be introduced more widely on campus, and more people will be learning how to use it. This is a very crucial step because the outcome of this phase could determine if UBC will decide to adopt LCA in the long term. If LCA is found to be beneficial, then plans can be made to implement LCA at UBC permanently.

LCA could eventually be institutionalized as a certification similar to LEED. Certain standards or benchmarks could be outlined, and buildings could be rated on many impact categories. If buildings attain a certain score, they could be presented with a plaque and a logo certifying the LCA performance.

7 Conclusion

The practice Life Cycle Assessment goes hand in hand with UBC's goals of becoming an environmentally friendly, world-class university. UBC has a requirement that new buildings must reach LEED Gold status, so LCA will become an invaluable tool to make this possible.

The study done in this report is a post-mortem LCA with the primary intention of providing a transparent strategic planning and educational tool for current and future building constructions at the UBC Vancouver campus. In order to achieve this result, all the UBC Academic Building LCA models developed by previous students were modified with the main assumption of a 60-year life service. A thorough description of the goal and scope of the study according to ISO 14044:2006 was developed as a means to help carry this study to the end. A section of the report was dedicated to giving the audience a general background on what has been done for development of the LCA models and study. Life cycle inventory (LCI) analysis and life cycle impact assessment (LCIA) analysis results were provided to demonstrate the environmental performance of the UBC Academic Buildings and the materials used in their constructions.

Since this study is also intended to help promote development of Life Cycle Assessment in the green building industry, every effort has been made to be as transparent and thorough as possible in developing this LCA study. All the supporting documents and files critical to carrying this study are either cited in the report or provided separately.

The most noteworthy findings from the study's life cycle inventory analysis and impact assessment are as follows:

- Approximately 232,000 Tonnes of concrete was used for the construction of all the buildings studied. This amount is equivalent to 81% of all the construction materials used.
- The amount of materials used for upper floor construction of all the buildings make up 38% of the total materials used.
- Roof construction is the primary hotspot within the buildings as it has the highest environmental impact of all elements.
- Delving deeper, the Product Stage (manufacturing, transportation, material extraction) was found to be the life cycle stage with the highest material impacts (i.e. the hotspots).

Next, the overall impact per square meter of all UBC Academic Buildings was benchmarked against the UBC baseline to show the overall percent performance of each building. Due to the significant nature of Global Warming, a construction cost analysis of all the buildings based on their CO_2 emission rates was also carried out. Among all the buildings constructed to LEED standards, the Centre for Interactive Research on Sustainability and Fred Kaiser were found to be good investments.

Finally the results of a sensitivity analysis for Math building is provided to give a general idea on which material properties or assembly types the impact basement results are most sensitive to. A thorough and detailed sensitivity analysis of all the buildings would allow for more sustainable alternatives when designing new buildings or renovating existing ones so that they can achieve LEED points.

LCA can be institutionalized on campus to greatly reduce the environmental impacts for decades to come. People can be educated about LCA through events, newsletters, or social media. Those interested in practicing LCA can learn about it in classes, workshops, or guest lecture events. LCA modelling tools and an LCI database will make the application of LCA more feasible. Eventually, LCA could become a part of UBC's environmental policy and a mandatory deliverable for building designs. With the use of LCA, the UBC campus will become a prime example of a green university, and will inspire many other campuses to do the same.

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Annex A – Author Reflection

Michael Elder

Discussion

I have had previous experience with sustainability in my past courses at UBC. Last year, I took CIVL 405 - Environmental Impact Studies. In that course, we learned about many different impacts and categories, and how to mitigate them. We also learned about legislation relating to environmental issues, and we did a detailed environmental case study on a potential construction project. I also took the CIVL 445 Capstone project course, where we were assigned to design a new building at the UBC Botanical Garden. I focused on the sustainability of the potential building. I read through many of LEED’s points requirements and stated how the building could achieve them.

Brief Course Overview

In CIVL 498C, we got an overview of the entire LCA process. We first learned about the history of LCA, and did an assignment to get familiarized with the concepts. Next, we learned about the terminology and the process of an LCA. We did an activity that involved the LCA concepts. We were then assigned to do an LCA of a building at UBC, and create a report.

Interest in Course

I was interested in this course because I enjoyed learning about sustainability in previous courses. In other courses, I only dealt with environmental impact assessment in a qualitative manner, but in this course we got to produce quantified impact results.

Observations

I’m interested in the future of LCA. I found it very interesting that LCA had so many potential social and economic impacts. The White Paper outlined the social impacts, so I may check on how those are coming along in the future.

Right now, most engineering students are deeply familiar with the concept of ‘sustainability’, but it seems that few students know a lot about LCA. Hopefully in the future, more courses about LCA are available. LCA is a good topic to learn because it involves many skills. There is a lot of data interpretation, decisions, calculations, and communication in the process. LCA also requires a knowledge database about environmental issues.

CEAB Graduate Attributes

	Name	Description	Select the content code most appropriate for each attribute from the dropdown menu	Comments on which of the CEAB graduate attributes you believe were addressed during your class experience. Reflect on the experiences you got from the games, lectures, assignments, quizzes, guest speakers organized for the class, and your final project experience.
1	**Knowledge Base**	Demonstrated competence in university level mathematics, natural sciences, engineering fundamentals, and specialized engineering knowledge appropriate to the program.	A = applied	We used mathematics and engineering knowledge in the LCA calculations.
2	**Problem Analysis**	An ability to use appropriate knowledge and skills to identify, formulate, analyze, and solve complex engineering problems in order to reach substantiated conclusions.	DA = developed & applied	We used problem analysis in the paper plane activity, and on a larger scale in the final project.
3	**Investigation**	An ability to conduct investigations of complex problems by methods that include appropriate experiments, analysis and interpretation of data, and synthesis of information in order to reach valid conclusions.	IDA = introduced, developed & applied	This was a key part of the course. A lot of investigation, interpretation, and synthesis of information were involved in the final project.

4	**Design**	An ability to design solutions for complex, open-ended engineering problems and to design systems, components or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations.	ID = introduced & developed	Design principles were involved in the institutionalization part of the report. We had to develop a solution for how LCA could be institutionalized at UBC.
5	**Use for Engineering Tools**	An ability to create, select, apply, adapt, and extend appropriate techniques, resources, and modern engineering tools to a range of engineering activities, from simple to complex, with an understanding of the associated limitations.	IA = introduced & applied	Engineering Tools were an important part of this course. We learned how to use Impact Estimator and were introduced to Tally.
6	**Individual and Team Work**	An ability to work effectively as a member and leader in teams, preferably in a multi-disciplinary setting.	A = applied	Individual work was done in Stage 1 and 2 of the project, and Stage 3 was done as a team. The paper plane activity was a team project.

7	**Communication**	An ability to communicate complex engineering concepts within the profession and with society at large. Such ability includes reading, writing, speaking and listening, and the ability to comprehend and write effective reports and design documentation, and to give and effectively respond to clear instructions.	DA = developed & applied	Communication is very important in this course, because we are creating a report that others may be using in the future.
8	**Professionalism**	An understanding of the roles and responsibilities of the professional engineer in society, especially the primary role of protection of the public and the public interest.	I = introduced	Professionalism is involved in the LCA, when keeping the interest of the public when making decisions.
9	**Impact of Engineering on Society and the Environment**	An ability to analyze social and environmental aspects of engineering activities. Such ability includes an understanding of the interactions that engineering has with the economic, social, health, safety, legal, and cultural aspects of society, the uncertainties in the prediction of such interactions; and the concepts of sustainable design and development and environmental stewardship.	IDA = introduced, developed & applied	This is the most important attribute. There are many categories of impacts, and our project put them into consideration.

10	**Ethics and Equity**	An ability to apply professional ethics, accountability, and equity.	I = introduced	Ethics and accountability should be considered when making an LCA.
11	**Economics and Project Management**	An ability to appropriately incorporate economics and business practices including project, risk, and change management into the practice of engineering and to understand their limitations.	ID = introduced & developed	We learned about how an LCA can provide economic benefits.
12	**Life-long Learning**	An ability to identify and to address their own educational needs in a changing world in ways sufficient to maintain their competence and to allow them to contribute to the advancement of knowledge.	I = introduced	We learned a bit about ways to get involved after university, like the Life Cycle Initiative.

Negar Panahi

Discussion

Prior to taking the CIVL 498C course, I have been exposed and have taken courses on sustainability. Coming from an architecture background, I have designed many green buildings and studied projects that are green and sustainable and had to meet certain LEED points. I have also read many articles and a couple of books on sustainability over the past few years. The very first book I read was The Ecology of Commerce" by Paul Hawken. Even though I have read briefly about the life cycle of different materials but was never really introduced to LCA studies.

Brief Course Overview

During this course, we were introduced to life cycle assessment and covered why it is an important topic. We covered LCA history, different impact categories, LCA terminology and processes, and uncertainty. Different activities, quizzes and assignments were given to us to better understand the topic. We also learned how to use Athena Impact Estimator and was also introduced to Tally software.

Interest in Course

Sustainability has always been an interest to me. During my architecture years, I enjoyed designing sustainable and green buildings. Taking this course has not only helped me fully understand the life cycle (cradle to grave) of materials, but has also helped me quantify impacts as well.

Observations

I enjoyed this project because it helped me think outside of the box and really understand LCA in different categories. I had to read a lot of outside sources and gather data in order to do this project.

I have always been interested in sustainability and green design and now LCA has become a huge interest to me. I am hoping to grow my knowledge in LCA and hopefully find a job that practices LCA studies. I believe that LCA is such an important topic for everyone with any educational background to understand.

I think this course needs to a mandatory course for at least engineering students at UBC and other universities. It is very important for engineers to understand LCA.

CEAB Graduate Attributes

	Name	Description	Select the content code most appropriate for each attribute from the dropdown menu	Comments on which of the CEAB graduate attributes you believe were addressed during your class experience. Reflect on the experiences you got from the games, lectures, assignments, quizzes, guest speakers organized for the class, and your final project experience.
1	**Knowledge Base**	Demonstrated competence in university level mathematics, natural sciences, engineering fundamentals, and specialized engineering knowledge appropriate to the program.	A = applied	I applied my mathematics, sustainability and architectural knowledge and background throughout the course and the assignments and deliverables. Coming from the architectural background helped me understand the concept.
2	**Problem Analysis**	An ability to use appropriate knowledge and skills to identify, formulate, analyze, and solve complex engineering problems in order to reach substantiated conclusions.	DA = developed & applied	I used my problem analysis skills for variety of activities throughout the course. I found the interactive in-class exercises helpful. They helped me become more of an analytical person and think outside of the box.
3	**Investigation**	An ability to conduct investigations of complex problems by methods that include appropriate experiments, analysis and interpretation of data, and synthesis of information in order to reach valid conclusions.	IDA = introduced, developed & applied	The topic and practice of LCA was introduced during the term, and there was a lot of investigation and interpretation used throughout the course, especially for the final project.

4	**Design**	An ability to design solutions for complex, open-ended engineering problems and to design systems, components or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations.	IA = introduced & applied	For the final project we had to come up with ideas and design solutions on how to institutionalize LCA at UBC
5	**Use for Engineering Tools**	An ability to create, select, apply, adapt, and extend appropriate techniques, resources, and modern engineering tools to a range of engineering activities, from simple to complex, with an understanding of the associated limitations.	IA = introduced & applied	Engineering tools, such as Athena Impact Estimator was used and applied in all the projects throughout this course. Learning this program was very valuable. Tally, Revit's plug-in, was also introduced to us.
6	**Individual and Team Work**	An ability to work effectively as a member and leader in teams, preferably in a multi-disciplinary setting.	A = applied	Individual work was done during Stages 1 and 2 of the project. The paper plane activity done in class and assignment 2 was a team work and the stage 3 was also a group work. Stage 3 was divided between each group members and followed by group meetings and group work.

7	**Communication**	An ability to communicate complex engineering concepts within the profession and with society at large. Such ability includes reading, writing, speaking and listening, and the ability to comprehend and write effective reports and design documentation, and to give and effectively respond to clear instructions.	IDA = introduced, developed & applied	Communication was an important factor of this course. LCA terminology was introduced and developed throughout the course. It is important to communicate clearly in this project, since the report maybe be used as future references.
8	**Professionalism**	An understanding of the roles and responsibilities of the professional engineer in society, especially the primary role of protection of the public and the public interest.	IDA = introduced, developed & applied	It is important to understand the need and interest of the public when doing an LCA study. In this project, all the assumptions and studies were professional.
9	**Impact of Engineering on Society and the Environment**	An ability to analyze social and environmental aspects of engineering activities. Such ability includes an understanding of the interactions that engineering has with the economic, social, health, safety, legal, and cultural aspects of society, the uncertainties in the prediction of such interactions; and the concepts of sustainable design and development and environmental stewardship.	IDA = introduced, developed & applied	Throughout the course and in out project, most categories of impacts were considered and studied. In order to have a more sustainable environment all these factors need to be considered.

10	**Ethics and Equity**	An ability to apply professional ethics, accountability, and equity.	A = applied	Professional and engineering ethics and equity has been applied to this report and throughout the course.
11	**Economics and Project Management**	An ability to appropriately incorporate economics and business practices including project, risk, and change management into the practice of engineering and to understand their limitations.	I = introduced	We learned about economic benefits and life cycle costing that comes from LCA studies.
12	**Life-long Learning**	An ability to identify and to address their own educational needs in a changing world in ways sufficient to maintain their competence and to allow them to contribute to the advancement of knowledge.	ID = introduced & developed	Being interested in the sustainability area, this course has helped me understand the full process of cradle to grave. I am hoping to grow my knowledge and knowledge of others in LCA and find a job that practices LCA.

Ali Salehi

Discussion

I was first introduced to the term “sustainability” in *CIVL 200 Engineering and Sustainable Development* by Dr. Susan Nesbit. When I took a project-based course, *CIVL 445 Engineering Design and Analysis,* I got to explore this topic more freely. I was to design a green roof for a multi storey commercial building in downtown Vancouver. Part of the project was to study the positive impacts of such a feature in a building on not only the environment but also people’s health and social life. I got more exposure to sustainability in a graduate level course (*CIVL 526 Virtual Design and Construction*) as part of a green building design. One of the primary goals of our project was to develop an environment friendly design for the soon-to-be-built Engineering Student Centre. Unfortunately at that time I did not have any knowledge of the Impact Estimator or Tally otherwise, I would have applied them in my project.

Brief Course Overview

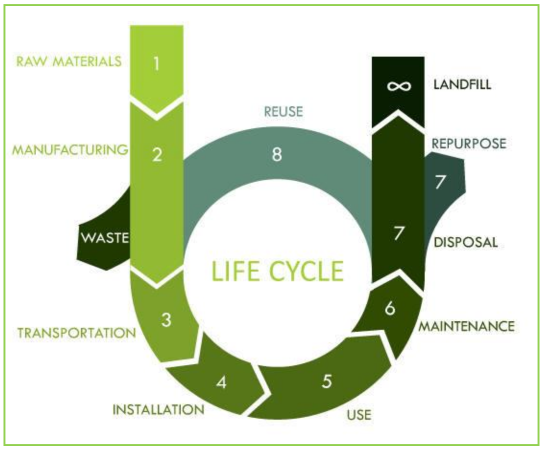
In CIVL 498C, we learned about the history and current state of LCA. We were introduced to major institutions and organizations involved in development of LCA. We got familiarized with ISO 14040 and 14044 (LCA standards which we used to develop our goal and scope accordingly) as well as environmental product declarations (EPDs). We also learned about LCA terminology and methodology as part of our LCA study and report. We gained working and introductory knowledge of different modeling tools such as Athena Impact Estimator and Tally. The different types of uncertainty associated with LCA were also covered as a part of an interactive in-class exercise. Finally, we were to utilize everything we learned to report on our own LCA study.

Interest in Course

I was interested in this course because I wanted to be more exposed to the green building industry. The background knowledge I had prior to enrolling in this course was limited to subjective and qualitative assessment of the sustainability state of a product. This course allowed me to think more objectively when it comes to sustainable design and decision-making.

Observations

I am interested in the future of LCA in the building industry as it will be the industry I will be working in. I have always been fascinated by green building designs and am looking forward to getting involved in such projects and gaining hands on experience. I found the incorporation of LCA into BIM modeling, even though at a conceptual level, to be very interesting and will most definitely follow up on that. I came across an interesting diagram[11] describing LCA as a “fragmented circle”.



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[11] Source: http://www.southwest-environmental.co.uk/

CEAB Graduate Attributes

	Name	Description	Select the content code most appropriate for each attribute from the dropdown menu	Comments on which of the CEAB graduate attributes you believe were addressed during your class experience. Reflect on the experiences you got from the games, lectures, assignments, quizzes, guest speakers organized for the class, and your final project experience.
1	**Knowledge Base**	Demonstrated competence in university level mathematics, natural sciences, engineering fundamentals, and specialized engineering knowledge appropriate to the program.	A = applied	I used my mathematics and engineering knowledge for in-class exercises throughout the course and mainly for the final report data analysis.
2	**Problem Analysis**	An ability to use appropriate knowledge and skills to identify, formulate, analyze, and solve complex engineering problems in order to reach substantiated conclusions.	DA = developed & applied	Throughout the course and project we were able to evaluate different information or situations, break them down into their key components, and analyze the different ways to solving them. These not only helped me to develop my analytical thinking skills but also pushed me into thinking more critically.
3	**Investigation**	An ability to conduct investigations of complex problems by methods that include appropriate experiments, analysis and interpretation of data, and synthesis of information in order to reach valid conclusions.	IDA = introduced, developed & applied	The final stage of the LCA study in this course involved a vast amount of information. Although analyzing them was frustrating at times, I found the outcome and the results to be intriguing.

4	**Design**	An ability to design solutions for complex, open-ended engineering problems and to design systems, components or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations.	DA = developed & applied	A main part of our study revolved around what we think of the future of LCA. In fact, this is what made our study more unique in comparison to previous studies in this course. We used our background knowledge as well as research skills to develop alternatives for solving the problem at-hand.
5	**Use for Engineering Tools**	An ability to create, select, apply, adapt, and extend appropriate techniques, resources, and modern engineering tools to a range of engineering activities, from simple to complex, with an understanding of the associated limitations.	IA = introduced & applied	Impact Estimator was the engineering tool that we were introduced to and used in carrying out the LCA study. We were also briefly introduced to other software such as SimaPro, On Screen Takeoff and Tally. I found Tally to be very interesting and would like to learn more about it.
6	**Individual and Team Work**	An ability to work effectively as a member and leader in teams, preferably in a multi-disciplinary setting.	A = applied	I liked the fact the project was divided in different stages. The first two were carried out individually, and the last part was group work. It allowed us to experience them both and assess the pros and cons of each. I take this as a life lesson.

7	**Communication**	An ability to communicate complex engineering concepts within the profession and with society at large. Such ability includes reading, writing, speaking and listening, and the ability to comprehend and write effective reports and design documentation, and to give and effectively respond to clear instructions.	DA = developed & applied	The outcome of this course is part of a future that is to be interpreted by our successors. Therefore, it was very crucial for us to communicate our results as transparent and as complete as possible. The study also involved an extensive amount of research that we made sure to give credit to through the application of APA formatting.
8	**Professionalism**	An understanding of the roles and responsibilities of the professional engineer in society, especially the primary role of protection of the public and the public interest.	IA = introduced & applied	Every effort was made in development of this study to be as transparent and as professional as possible.
9	**Impact of Engineering on Society and the Environment**	An ability to analyze social and environmental aspects of engineering activities. Such ability includes an understanding of the interactions that engineering has with the economic, social, health, safety, legal, and cultural aspects of society, the uncertainties in the prediction of such interactions; and the concepts of sustainable design and development and environmental stewardship.	IDA = introduced, developed & applied	This study focused primarily on various facets of LCA such as health, environmental, and economic. Throughout the course, we were also introduced to social and legal aspects of LCA which we did not get to apply to our study as much as others.

10	**Ethics and Equity**	An ability to apply professional ethics, accountability, and equity.	A = applied	Professional ethics were applied in carrying out the study and preparing the report.
11	**Economics and Project Management**	An ability to appropriately incorporate economics and business practices including project, risk, and change management into the practice of engineering and to understand their limitations.	I = introduced	We were introduced to Life Cycle Costing so not to confuse it with Life Cycle Assessment. There is no doubt that these two overlap with each other so often that combined can be referred to as Life Cycle Analysis. I believe that LCC was neither developed nor applied in this study.
12	**Life-long Learning**	An ability to identify and to address their own educational needs in a changing world in ways sufficient to maintain their competence and to allow them to contribute to the advancement of knowledge.	I = introduced	I took this course as an elective to get more familiar with green building designs. By the end of the course, not it broaden my knowledge of this topic, it also helped me to enhance my social inclusion and self-sustainability.

Annex B – Impact Category Descriptions

Impact Category Definitions

This section briefly describes the nine environmental measures used to summarize the environmental assessment results provided by the Impact Estimator Version 5.0.01.

Acidification Potential (AP)

Acidification is a more regional rather than global impact effecting human health when high concentrations of NOx and SO2 are attained. The AP of an air or water emission is calculated on the basis of its H+ equivalence effect on a mass basis.

Aquatic Eutrophication Potential

Eutrophication is the fertilization of surface waters by nutrients that were previously scarce. When a previously scarce or limiting nutrient is added to a water body it leads to the proliferation of aquatic photosynthetic plant life. This may lead to a chain of further consequences ranging from foul odours to the death of fish. The calculated result is expressed on an equivalent mass of nitrogen (N) basis.

Global Warming Potential (GWP)

Global warming potential is a reference measure. The methodology and science behind the GWP calculation can be considered one of the most accepted LCIA categories. GWP will be expressed on an equivalency basis relative to CO2 – in kg or tonnes CO2 equivalent.

Carbon dioxide is the common reference standard for global warming or greenhouse gas effects. All other greenhouse gases are referred to as having a "CO2 equivalence effect" which is simply a multiple of the greenhouse potential (heat trapping capability) of carbon dioxide. This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time.

As yet, no consensus has been reached among policy makers about the most appropriate time horizon for greenhouse gas calculations. The International Panel on Climate Change100-year time horizon figures have been used here as a basis for the equivalence index:

CO2 Equivalent kg = CO2 kg + (CH4 kg x 28) + (N2O kg x 265)

A recent IPCC report, "CLIMATE CHANGE 2013 The Physical Science Basis" provided an updated list of GWP equivalence factors, that have not as yet been updated (June 2014) in TRACI, but the Impact

Estimator includes updated values for nine of the most common GWP contirbutors (Methane, Nitrous Oxide (N_2O), CFC-11, CFC-12, HCFC-22, HCFC-141b, HCFC-142b, HFC-134a and Sulphur Hexaflouride). When the EPA publishes an updated list of TRACI characterization factors, the Impact Estimator will be updated with all the new factors.

While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modelling manufacturing process stages. One example where process CO_2 emissions are significant is in the production of cement (calcination of limestone). Because the Impact Estimator uses data developed by a detailed life cycle modelling approach, all relevant process emissions of greenhouse gases are included in the resultant global warming potential index.

Human Health (HH) Criteria Air-Mobile

Particulate matter of various sizes (PM10 and PM2.5) have a considerable impact on human health. The EPA has identified "particulates" (from diesel fuel combustion) as the number one cause of human health deterioration due to its impact on the human respiratory system – asthma, bronchitis, acute pulmonary disease, etc. It should be mentioned that particulates are an important environmental output of plywood product production and need to be traced and addressed. The Institute used TRACI’s "Human Health Particulates from Mobile Sources" characterization factor, on an equivalent PM2.5 basis, in our final set of impact indicators.

Ozone Depletion Potential (ODP)

Stratospheric ozone depletion potential accounts for impacts related to the reduction of the protective ozone layer within the stratosphere caused by emissions of ozone depleting substances (CFCs, HFCs, and halons). The ozone depletion potential of each of the contributing substances is characterized relative to CFC-11, with the final impact indicator indicating mass (e.g., kg) of equivalent CFC-11.

Photochemical Ozone Formation Potential (Smog)

Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical ozone creation potential (POCP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x). The “smog” indicator is expressed on a mass of equivalent O_3 basis.

Total Primary Energy

Total Primary Energy Consumption is reported in mega-joules (MJ) at the bottom of the Energy Consumption absolute value table as well as the Detailed and Condensed Summary Measure tables. Embodied primary energy includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources. (For example, natural gas used as a raw material in the production of various plastic (polymer) resins.) In addition, the Impact Estimator captures the indirect energy use associated with processing, transporting, converting and delivering fuel and energy. If the user inputs Operating Energy Consumption, it will also be included in Total Primary Energy.

Non-Renewable Energy

Non-Renewable Energy is a subtotal of Total Primary Energy, by energy type, that includes all fossil fuel energies and nuclear energy.

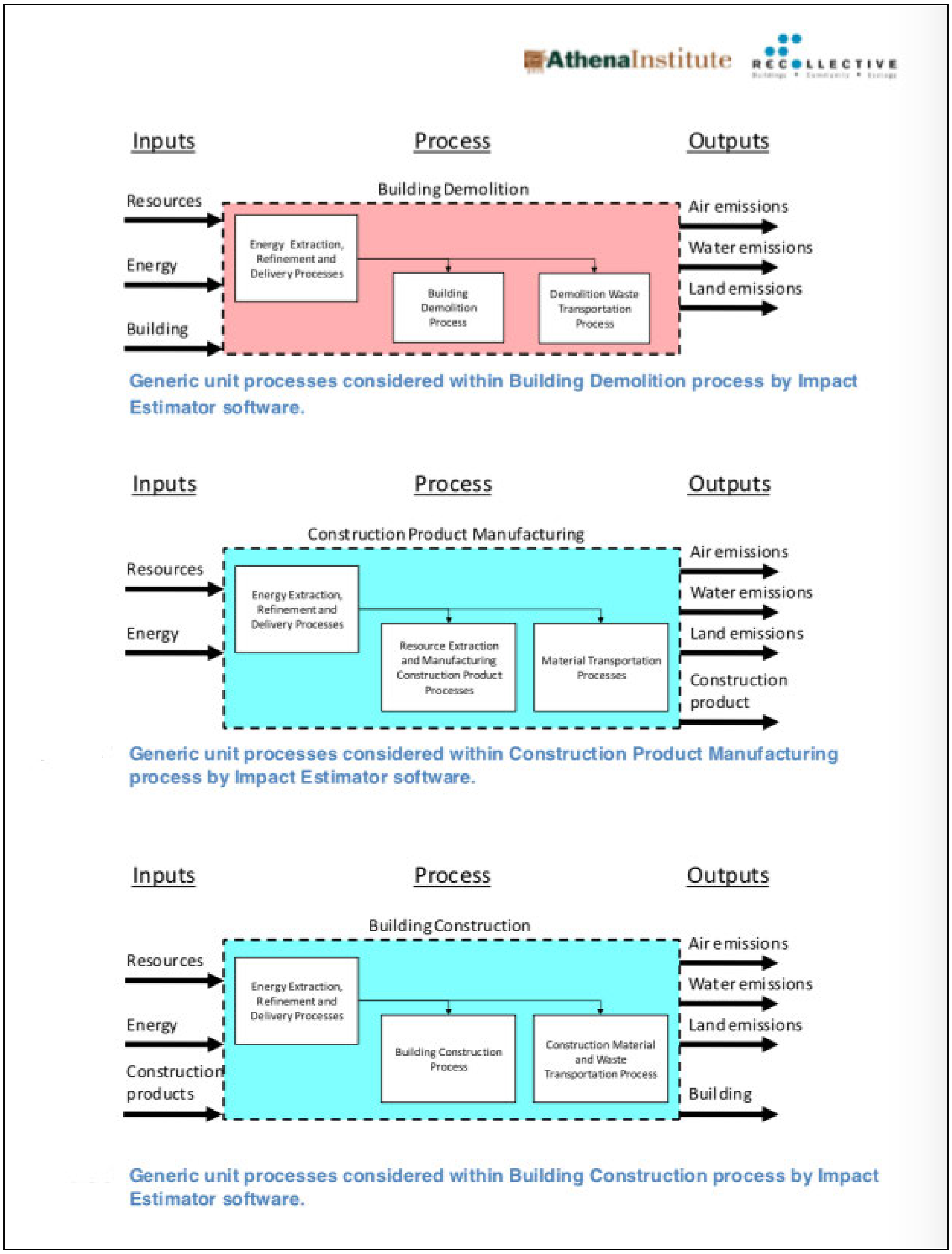
Fossil Fuel Consumption

Fossil Fuel Consumption is a subtotal of Total Primary Energy, by energy type, that includes all fossil fuel energies.

Annex C – Inputs and Outputs of Three Processes

The unit processes and inputs and outputs considered within these three main processes are outlined below.

Figure 8: Generic Unit Processes Considered Within Processes by Impact Estimator



Source: (Athena Institute, 2011)

Annex D – Table of Uncertainties

The following table is taken directly from the Lasserre Building LCA Study (by Andrew Russell in 2013) for educational purposes only[12]. The table provides explanations and examples for different types of uncertainty.

Table 6: Types of Uncertainties in LCA Study

Type of Uncertainty	**Sources of Uncertainty**	**Example within LCI Databases**
Data	Collection, allocation procedures (mass or economic), inaccurate or missing data, lifetimes of substances, travel potential in impacts (eutrophication , acidification	Travel potential exists as TRACI acidification category developed on U.S. empirical models with specific location.22 Vancouver weather and geography different, resulting in uncertainty with travel potential
Model	Linear vs. non-linear model (increasing, constant or decreasing returns?) Characterization factors inaccurate or not known	As Athena and US LCI databases are young (10-15 years), the models are still improving as years of data strengthen them
Temporal	Differences in seasonal factory emissions, e.g. Sawmill lumber diameter changing from winter to summer. Data vintage. Climate effect on impact severity (temp).	Lasserre built with vintage 1960's materials, transport, energy, processing and construction techniques but Athena and US LCI use current data.
Spatial	Regional differences (factories, energy mix, preferred transport), regional environment sensitivity, distribution of emissions (plane vs. factory)	Athena uses North American industry averages for construction materials. Some Lasserre materials may be international (China, Japan, and Europe). TRACI assumes North American context for characterization factors while some impacts may be felt elsewhere in production chain like bauxite extraction in Australia.
Variability between Sources	Differences between factory practices and standards. Human exposure patterns (sawmill workers vs. residents nearby, elderly vs. youth)	Athena assumes similar Human exposure to process when worker would have much higher exposure to paint than occupant once dry.

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[12] All the credits go to the original author of the table.

Annex E – Elemental Construction Format

CIVL 498C Elemental Construction Format

The following table illustrates the building elements included in this LCA study. Note that A12 Backfill and Excavation are out of scope of this LCA study.

Table 7: CIVL 498C Elemental Construction Format

Level 3 Elements included in CIVL 498C Final Project	Other CIQS Level 3 Elements to be included for CIVL 498C Final Projects	Units	Description of what to measure
A11 Foundations	A12 Shoring	m^2	Total area of the slab-on-grade.
A21 Lowest Floor Construction		m^2	Total area of the slab-on-grade.
A22 Upper Floor Construction		m^2	Sum of the total area of all upper floor(s) measured from the outside face of the exterior walls.
A23 Roof Construction	A34 Eaves Soffit A34 Fascia A34 Skylight, A34 Roof Finish, A34 Flashing and Coping, A34 Trafficable roof surface,	m^2	Sum of total area of the roof(s) measured from the outside face of the exterior walls.
A31 Walls Below Grade		m^2	Sum of total surface area of the exterior walls below grade.
A32 Walls Above Grade	A33 Exterior Doors & Screens A35 Parapet wall A35 Projections, Balconies, Canopies, Sunshades A35 Insulated Soffit	m^2	Sum of total surface area of the exterior walls above grade.
B11 Partitions	B12 Interior Doors Frames & Hardware	m^2	Sum of total surface area of the interior walls.

Source: CIVL 498C 2014 Course Materials

Annex F – Inventory Analysis Results

Table 8: Elemental and Whole Building Bill of Materials

ID	Material	Units	Whole Building	A11	A21	A22	A23	A31	A32	B11
1	#15 Organic Felt	Tonnes	148.17	0.00	0.00	22.34	118.36	0.14	7.16	0.17
2	1/2" Gypsum Fibre Gypsum Board	Tonnes	100.36	0.00	0.00	13.00	0 00	0.00	21.10	66 25
3	1/2" Moisture Resistant Gypsum Board	Tonnes	95.41	0.00	0.00	0.00	35.28	5.78	18.61	35.74
4	1/2" Regular Gypsum Board	Tonnes	1047.97	0.17	0.00	0.79	0.79	48.99	362.98	634 25
5	3 mil Polyethylene	Tonnes	1 05	0.00	0.08	0.00	0 35	0.24	0.33	0 05
6	5/8" Fire-Rated Type X Gypsum Board	Tonnes	341.17	0.00	0.00	0.00	0 00	0.00	0.00	341.17
7	5/8" Gypsum Fibre Gypsum Board	Tonnes	0 31	0.00	0.00	0.00	0.00	0.31	0.00	0 00
8	5/8" Moisture Resistant Gypsum Board	Tonnes	205.14	0.00	0.00	0.00	77.37	0.00	108.44	19 33
9	5/8" Regular Gypsum Board	Tonnes	1073.85	8.03	27.67	75.97	0.00	96.94	143.62	721.62
10	6 mil Polyethylene	Tonnes	14.10	0.87	2.97	0.00	3.82	1.75	4.27	0.42
11	8" Concrete Block	Tonnes	11856.07	0.00	0.00	95.24	7.24	190.91	2750.06	8812.61
12	Air Barrier	Tonnes	0.17	0.00	0.00	0.00	0.00	0.00	0.17	0 00
13	Aluminum	Tonnes	223.23	0.00	0.00	0.00	6.08	0.67	176.49	39 99
14	Aluminum Clad Wood Window Frame	Tonnes	2.28	0.00	0.00	0.00	0.00	0.00	2.28	0 00
15	Aluminum Window Frame	Tonnes	55.47	0.00	0.00	0.00	0.00	5.83	47.77	1 87
16	Ballast (aggregate stone)	Tonnes	4552.78	0.00	0.00	367 81	3063.98	0.00	1120.99	0 00
17	Blown Cellulose	Tonnes	4.84	0.00	0.00	0 00	4.84	0.00	0.00	0 00
18	Cedar Wood Bevel Siding	Tonnes	2.27	0.00	0.00	0 00	0.00	0.00	0.79	1.48
19	Cedar Wood Shiplap Siding	Tonnes	165.00	0.00	24.21	23 58	67.35	1.14	48.73	0 00
20	Cold Rolled Sheet	Tonnes	8.38	0.00	0.00	0 80	1.45	0.41	5.21	0 51
21	Concrete 20 MPa (flyash 35%)	Tonnes	2583.84	152.82	0.00	1453.79	0.00	243.06	0.00	734.17
22	Concrete 20 MPa (flyash av)	Tonnes	74681.75	23027.50	8510.59	11607.72	6428.71	4740.28	8109.67	12257 28
23	Concrete 30 MPa (flyash 25%)	Tonnes	11081.11	712.04	685.60	9259 07	424.40	0.00	0.00	0 00
24	Concrete 30 MPa (flyash 35%)	Tonnes	4563.98	1392.54	533.33	0 00	0.00	2200.57	160.41	277.12
25	Concrete 30 MPa (flyash av)	Tonnes	121065.90	13112.22	5601.05	66100 90	12656.02	6723.85	13409.31	3462 56
26	Concrete 60 MPa (flyash av)	Tonnes	691.94	0.00	0.00	0 00	0.00	691.94	0.00	0 00
27	Concrete Brick	Tonnes	1852.19	0.00	0.00	0 00	0.00	251.42	1390.48	210 29
28	Concrete Tile	Tonnes	0.00	0.00	0.00	0 00	0.00	0.00	0.00	0 00
29	Double Glazed Hard Coated Air	Tonnes	33.75	0.00	0.00	0 00	0.00	0.00	33.75	0 00
30	Double Glazed Hard Coated Argon	Tonnes	0.00	0.00	0.00	0 00	0.00	0.00	0.00	0 00
31	Double Glazed No Coating Air	Tonnes	353.73	0.00	0.00	0 00	0.00	65.90	250.42	37.41
32	Double Glazed Soft Coated Argon	Tonnes	10.95	0.00	0.00	0 00	0.00	0.00	10.95	0 00
33	EPDM membrane (black, 60 mil)	Tonnes	8.56	0.00	0.00	0 00	0.24	0.00	6.84	1.48
34	Expanded Polystyrene	Tonnes	27.76	0.00	0.00	0 00	3.69	7.04	16.61	0.43
35	Extruded Polystyrene	Tonnes	127.50	0.00	0.00	21.18	44.60	5.67	49.10	6 96
36	FG Batt R11-15	Tonnes	58.53	0.01	0.00	0.00	0.00	4.23	16.80	37.49
37	FG Batt R20	Tonnes	0.51	0.00	0.00	0.00	0.15	0.00	0.36	0 00
38	Fiber Cement	Tonnes	13.76	0.00	0.00	0.00	0.00	0.00	13.76	0 00

ID	Material	Units	Whole Building	A11	A21	A22	A23	A31	A32	B11
39	Galvanized Decking	Tonnes	88.84	0.00	0.00	0.00	88.84	0.00	0.00	0.00
40	Galvanized Sheet	Tonnes	257.36	0.00	0.33	4.06	24.63	16.33	42.40	169.61
41	Galvanized Studs	Tonnes	459.97	0.00	0.00	0.00	156.95	29.28	85.34	188.39
42	Glass Facer	Tonnes	1.45	0.00	0.00	0.00	1.45	0.00	0.00	0.00
43	Glazing Panel	Tonnes	1013.87	0.00	0.00	0.00	27.53	1.70	814.93	169.70
44	GluLam Sections	Tonnes	331.84	0.00	0.00	137.88	193.96	0.00	0.00	0.00
45	Hollow Structural Steel	Tonnes	73.46	0.00	0.00	52.49	20.97	0.00	0.00	0.00
46	Joint Compound	Tonnes	277.52	0.80	2.68	8.63	6.82	16.13	49.99	192.47
47	Laminated Veneer Lumber	Tonnes	168.66	0.00	0.00	36.48	132.18	0.00	0.00	0.00
48	Large Dimension Softwood Lumber, kiln-dried	Tonnes	159.73	0.00	23.91	82.76	53.07	0.00	0.00	0.00
49	MBS Metal Roof Cladding - Commercial (26 Ga.)	Tonnes	20.58	0.00	0.00	0.00	20.58	0.00	0.00	0.00
50	MBS Metal Wall Cladding - Commercial (24 Ga.)	Tonnes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
51	MDI resin	Tonnes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
52	Metal Wall Cladding - Commercial (26 Ga.)	Tonnes	28.29	0.00	0.00	0.00	0.00	2.88	25.41	0.00
53	Metal Wall Cladding - Residential (30 Ga.)	Tonnes	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.66
54	Metric Modular (Modular) Brick	Tonnes	3149.58	0.00	0.00	0.00	0.00	36.42	2759.55	353.61
55	Modified Bitumen membrane	Tonnes	336.06	0.00	0.00	0.00	336.06	0.00	0.00	0.00
56	Mortar	Tonnes	13550.34	0.00	0.00	122.28	1.55	308.37	4333.54	8784.60
57	MW Batt R11-15	Tonnes	65.43	0.00	0.00	0.00	44.86	0.00	6.76	13.81
58	Nails	Tonnes	42.02	0.01	0.36	1.44	10.53	1.93	6.32	21.42
59	Natural Stone	Tonnes	59.10	0.00	0.00	0.00	0.00	0.00	59.10	0.00
60	Ontario (Standard) Brick	Tonnes	783.25	0.00	0.00	0.00	0.00	84.36	578.20	120.69
61	Open Web Joists	Tonnes	83.25	0.00	0.00	0.00	83.25	0.00	0.00	0.00
62	Oriented Strand Board	Tonnes	32.32	0.00	0.00	0.00	0.00	0.00	15.04	17.28
63	Paper Tape	Tonnes	3.18	0.01	0.03	0.10	0.08	0.19	0.57	2.21
64	Parallel Strand Lumber	Tonnes	154.10	0.00	0.00	154.10	0.00	0.00	0.00	0.00
65	Polyethylene Filter Fabric	Tonnes	1.81	0.00	0.00	0.46	1.36	0.00	0.00	0.00
66	Polyiso Foam Board (unfaced)	Tonnes	41.75	0.00	0.00	2.43	39.31	0.00	0.00	0.00
67	Precast Concrete	Tonnes	16423.73	0.00	0.00	14417.06	2006.67	0.00	0.00	0.00
68	PVC Membrane 48 mil	Tonnes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
69	Rebar, Rod, Light Sections	Tonnes	8396.01	73.33	144.31	4929.33	804.26	262.07	810.09	1372.61
70	Roofing Asphalt	Tonnes	755.62	0.00	0.00	45.20	710.41	0.00	0.00	0.00
71	Screws Nuts & Bolts	Tonnes	27.52	0.00	0.00	0.26	3.28	1.90	10.31	11.78
72	Small Dimension Softwood Lumber, kiln-dried	Tonnes	389.13	0.00	0.00	3.08	6.57	16.67	79.27	283.54
73	Softwood Plywood	Tonnes	83.71	0.00	0.00	29.08	0.89	6.06	26.38	21.32
74	Solvent Based Alkyd Paint	Tonnes	0.82	0.00	0.00	0.00	0.00	0.13	0.34	0.34
75	Solvent Based Varnish	Tonnes	0.03	0.00	0.00	0.00	0.00	0.00	0.02	0.00

ID	Material	Units	Whole Building	A11	A21	A22	A23	A31	A32	B11
76	Spandrel Panel	Tonnes	30.72	0.00	0.00	0 00	0.77	0.00	22.42	7 54
77	Stucco over metal mesh	Tonnes	153.32	0.00	0.00	0 00	0.00	6.17	139.64	7 52
78	Stucco over porous surface	Tonnes	567.27	0.00	0.00	2 39	0.00	33.06	268.50	263 33
79	Type III Glass Felt	Tonnes	107.15	0.00	0.00	0 00	107.15	0.00	0.00	0 00
80	Unclad Wood Window Frame	Tonnes	21.88	0.00	0.00	0 00	0.00	1.05	20.83	0 00
81	Vinyl Siding	Tonnes	0.81	0.00	0.00	0 00	0.00	0.00	0.81	0 00
82	Water Based Latex Paint	Tonnes	25.53	0.00	1.47	1.44	4.10	0.26	6.89	11 37
83	Welded Wire Mesh / Ladder Wire	Tonnes	135.03	9.83	40.17	73 33	11.71	0.00	0.00	0 00
84	Wide Flange Sections	Tonnes	7.59	0.00	0.00	0.66	6.93	0.00	0.00	0 00

Table 9: Level 3 CIQS Elemental Descriptions

Reference Flows: CIVL 498C Level 3 Elemental Format	Description
A11 Foundations	Strip and Pad Footings
A21 Lowest Floor Construction	Slab on grade on lowest floor
A22 Upper Floor Construction	Columns, beams, suspended slab floors, stairs
A23 Roof Construction	Supporting Columns and beams, roof slab
A31 Walls Below Grade	Exterior below grade walls
A32 Walls Above Grade	Exterior above grade walls
B11 Partitions	All interior walls

Annex G – Material Categorization Index

Figure 9: Material Categories Used in the Study

Material
#15 Organic Felt
1/2" Gypsum Fibre Gypsum Board
1/2" Moisture Resistant Gypsum Board
1/2" Regular Gypsum Board
3 mil Polyethylene
5/8" Fire-Rated Type X Gypsum Board
5/8" Gypsum Fibre Gypsum Board
5/8" Moisture Resistant Gypsum Board
5/8" Regular Gypsum Board
6 mil Polyethylene
8" Concrete Block
Air Barrier
Aluminum
Aluminum Clad Wood Window Frame
Aluminum Window Frame
Ballast (aggregate stone)
Blown Cellulose
Cedar Wood Bevel Siding
Cedar Wood Shiplap Siding
Cold Rolled Sheet
Concrete 20 MPa (flyash 35%)
Concrete 20 MPa (flyash av)
Concrete 30 MPa (flyash 25%)
Concrete 30 MPa (flyash 35%)
Concrete 30 MPa (flyash av)
Concrete 60 MPa (flyash av)
Concrete Brick
Concrete Tile
Double Glazed Hard Coated Air
Double Glazed Hard Coated Argon
Double Glazed No Coating Air
Double Glazed Soft Coated Argon
EPDM membrane (black, 60 mil)
Expanded Polystyrene
Extruded Polystyrene
FG Batt R11-15
FG Batt R20
Fiber Cement
Galvanized Decking
Galvanized Sheet
Galvanized Studs
Glass Facer
Glazing Panel
GluLam Sections
Hollow Structural Steel
Joint Compound
Laminated Veneer Lumber
Large Dimension Softwood Lumber, kiln-dried
MBS Metal Roof Cladding - Commercial (26 Ga.)
MBS Metal Wall Cladding - Commercial (24 Ga.)
MBS Metal Wall Cladding - Commercial (24 Ga.)
MDI resin
Metal Wall Cladding - Commercial (26 Ga.)
Metal Wall Cladding - Residential (30 Ga.)
Metric Modular (Modular) Brick
Modified Bitumen membrane
Mortar
MW Batt R11-15
Nails
Natural Stone
Ontario (Standard) Brick
Open Web Joists
Oriented Strand Board
Paper Tape
Parallel Strand Lumber
Polyethylene Filter Fabric
Polyiso Foam Board (unfaced)
Precast Concrete
PVC Membrane 48 mil
Rebar, Rod, Light Sections
Roofing Asphalt
Screws Nuts & Bolts
Small Dimension Softwood Lumber, kiln-dried
Softwood Plywood
Solvent Based Alkyd Paint
Solvent Based Varnish
Spandrel Panel
Stucco over metal mesh
Stucco over porous surface
Type III Glass Felt
Unclad Wood Window Frame
Vinyl Siding
Water Based Latex Paint
Welded Wire Mesh / Ladder Wire
Wide Flange Sections

Material Category
Wood
Wall Coverings
Metal
Roof Materials
Masonry/Bricks
Concrete
Insulation
Glass
Plastics
Miscellaneous

Annex H – Impact Assessment Results

Table 10: Sum of Total Impacts per square meter

Sum of Total Impacts per m2									
Impact Category	**Units**	**A11**	**A21**	**A22**	**A23**	A31	**A32**	**B11**	**Whole Building**
Global Warming Potential	kg CO2 eq	2.64E+03	1.14E+03	4.44E+03	5.64E+03	2.05E+03	3.39E+03	3.30E+03	8.72E+03
Acidification Potential	kg SO2 eq	1.81E+01	7.91E+00	2.79E+01	3.44E+01	1.37E+01	2.44E+01	2.16E+01	5.72E+01
HH Particulate	kg PM2.5 eq	5.95E+00	2.63E+00	1.22E+01	1.76E+01	4.58E+00	1.50E+01	9.63E+00	2.70E+01
Eutrophication Potential	kg N eq	8.51E-01	4.46E-01	1.67E+00	1.12E+01	7.74E-01	3.13E+00	1.29E+00	6.65E+00
Ozone Depletion Potential	kg CFC-11 eq	1.23E-05	4.10E-06	1.90E-05	2.78E-05	1.08E-05	1.86E-05	1.23E-05	4.10E-05
Smog Potential	kg O3 eq	4.47E+02	1.96E+02	6.31E+02	6.93E+02	3.05E+02	4.19E+02	4.37E+02	1.19E+03
Total Primary Energy	MJ	2.18E+04	1.04E+04	4.98E+04	1.19E+05	2.07E+04	1.03E+05	5.54E+04	1.49E+05
Non-Renewable Energy	MJ	2.02E+04	9.59E+03	4.69E+04	1.14E+05	1.94E+04	9.88E+04	5.27E+04	1.41E+05
Fossil Fuel Consumption	MJ	1.96E+04	9.05E+03	3.80E+04	9.62E+04	1.74E+04	3.10E+04	2.91E+04	8.67E+04

Table 11: Average Total Impacts per square meter

Mean of Total Impacts per m2									
Impact Category	**Units**	**A11**	**A21**	**A22**	**A23**	A31	**A32**	**B11**	**Whole Building**
Global Warming Potential	kg CO2 eq	1.20E+02	5.18E+01	2.02E+02	2.56E+02	9.78E+01	1.54E+02	1.50E+02	3.96E+02
Acidification Potential	kg SO2 eq	8.21E-01	3.59E-01	1.27E+00	1.56E+00	6.51E-01	1.11E+00	9.81E-01	2.60E+00
HH Particulate	kg PM2.5 eq	2.71E-01	1.20E-01	5.55E-01	8.00E-01	2.18E-01	6.82E-01	4.38E-01	1.23E+00
Eutrophication Potential	kg N eq	3.87E-02	2.03E-02	7.61E-02	5.07E-01	3.69E-02	1.42E-01	5.86E-02	3.02E-01
Ozone Depletion Potential	kg CFC-11 eq	5.59E-07	1.86E-07	8.62E-07	1.26E-06	5.12E-07	8.46E-07	5.61E-07	1.86E-06
Smog Potential	kg O3 eq	2.03E+01	8.92E+00	2.87E+01	3.15E+01	1.45E+01	1.90E+01	1.98E+01	5.42E+01
Total Primary Energy	MJ	9.93E+02	4.72E+02	2.26E+03	5.39E+03	9.84E+02	4.70E+03	2.52E+03	6.77E+03
Non-Renewable Energy	MJ	9.19E+02	4.36E+02	2.13E+03	5.16E+03	9.26E+02	4.49E+03	2.40E+03	6.43E+03
Fossil Fuel Consumption	MJ	8.92E+02	4.11E+02	1.73E+03	4.37E+03	8.31E+02	1.41E+03	1.32E+03	3.94E+03

Table 12: Total Impact per square meter for All Life Cycle Stages

		PRODUCT (A1 to A3) per m2			**CONSTRUCTION PROCESS (A4 & A5) per m2**			**USE (B2, B4 & B6) per m2**			**END OF LIFE (C1 to C4) per m2**		
Impact Category	**Units**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	**Total**	De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**
Global Warming Potential	**kg CO2 eq**	6,672.43	187.02	**6,858.24**	451.11	446.13	**897.20**	475.65	23.03	**498.56**	300.26	163.65	**463.87**
Acidification Potential	**kg SO2 eq**	39.41	1.86	**41.06**	3.38	4.24	**7.61**	2.88	0.22	**3.10**	3.72	1.48	**5.19**
HH Particulate	**kg PM2.5 eq**	21.64	0.10	**21.74**	0.74	0.24	**0.98**	3.96	0.01	**3.98**	0.21	0.09	**0.30**
Eutrophication Potential	**kg N eq**	1.44	0.13	**1.57**	0.18	0.29	**0.47**	4.26	0.02	**4.27**	0.25	0.10	**0.35**
Ozone Depletion Potential	**kg CFC-11 eq**	3.52E-05	6.46E-09	**3.52E-05**	1.43E-06	1.55E-08	**1.42E-06**	4.33E-06	7.86E-10	**4.34E-06**	1.17E-08	5.35E-09	**1.70E-08**
Smog Potential	**kg O3 eq**	656.15	64.73	**720.81**	93.40	147.44	**240.82**	39.28	7.82	**47.10**	131.05	51.25	**182.31**
Total Primary Energy	**MJ**	116,057.96	2,817.52	**118,867.17**	5,098.28	5,779.98	**10,876.45**	12,353.01	307.41	**12,659.74**	4,523.62	1,996.76	**6,518.87**
Non-Renewable Energy	**MJ**	109,848.30	2,816.53	**112,688.35**	4,833.80	5,777.54	**10,605.83**	11,494.42	307.32	**11,802.44**	4,372.57	1,995.39	**6,367.73**
Fossil Fuel Consumption	**MJ**	56,518.18	2,811.88	**59,331.61**	4,634.81	5,768.35	**10,401.70**	10,340.86	306.76	**10,648.07**	4,356.62	1,991.19	**6,348.68**

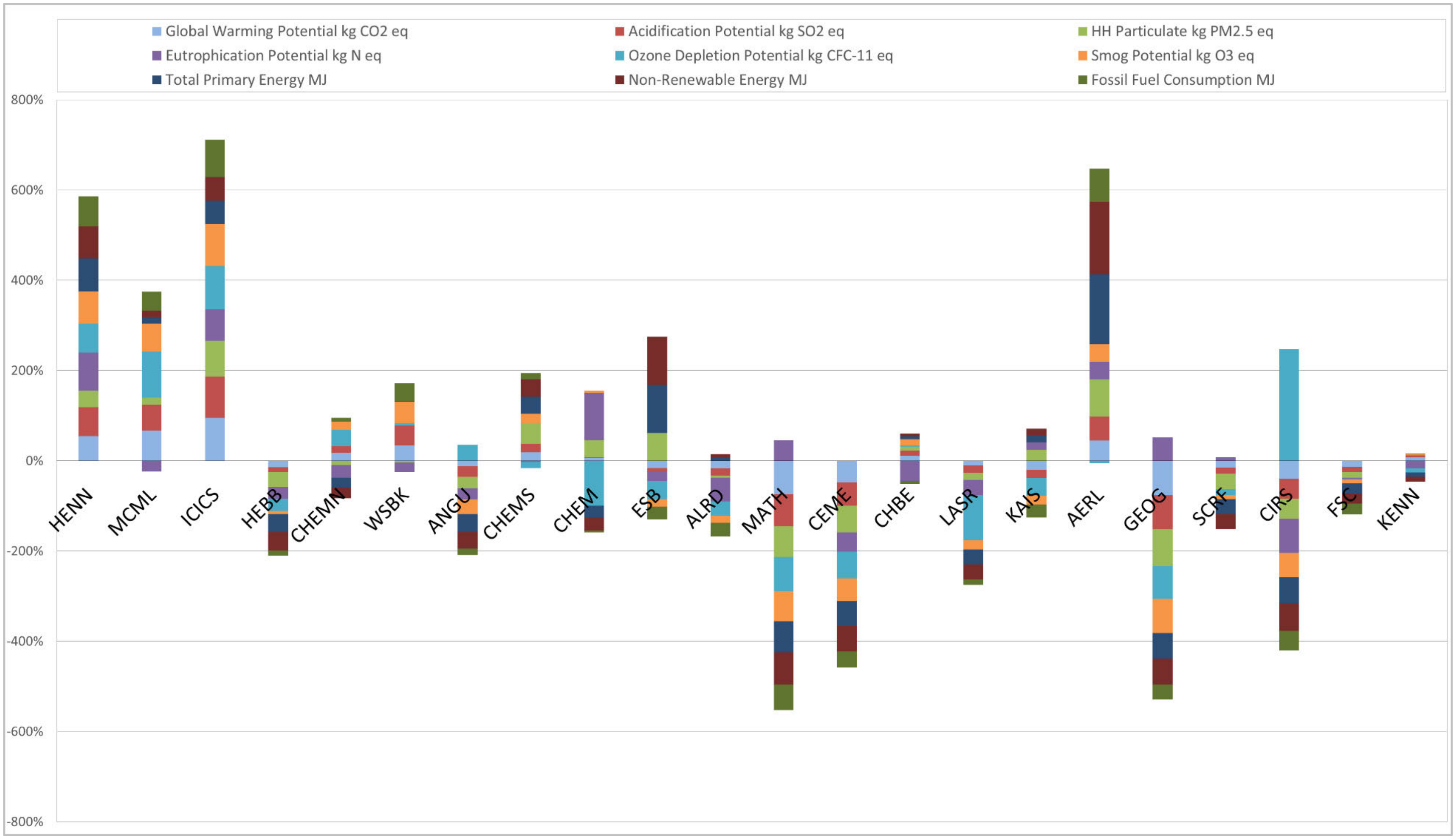
Annex I – UBC Academic Building Profiles

Table 13: Profile of UBC Academic Buildings in the Study

Element	Unit	HENN	MCML	ICICS	HEBB	CHEMN	WSBK	ANGU	CHEMS	CHEM	ESB	ALRD
Cost	$	-	$67,719,000.00	$67,719,000.00	$10,450,631.51	$10,000,000.00	$36,698,519.00	$87,307,309.00	$1,659,655.00	$12,800,000.00	$75,000,000.00	$56,560,000.00
A11 Foundations	m2	1217	3292	2151	369	616	2510	1522	1217	1,654	1178	2506.55
A21 Lowest Floor Construction	m2	1217	3292	2151	1898	616	2510	1522	1217	1,654	1178	2506.55
A22 Upper Floor Construction	m2	2635	8962	3543	3879	1199	3182	6473	2635	5,796	7524.7	9710.5
A23 Roof Construction	m2	1202	2987	1387	1411	332	222	2351	1202	1,802	708	7439.4
A31 Walls Below Grade	m2	737	2515	424	1050	707	833	635	737	1,723	1953.7	7542.2
A32 Walls Above Grade	m2	2047	4118	2373	3723	1296	3182	3280	2047	3,988	6221.9	6639.5
B11 Partitions	m2	1161	13664	9629	1296	1925	2026	6073	1161	8,481	9863.1	9679
Whole Building	m2	3851	12254	5694	5777	1815	5692	7995	3851	7450	8703	12217
Element	**Unit**	**MATH**	**CEME**	**CHBE**	**LASR**	**KAIS**	**AERL**	**GEOG**	**SCRF**	**KENN**	**CIRS**	**FSC**
Cost	$	$932,618.26	$6,700,000.00	$36,675,628.00	$34,600,000.00	$33,889,182.00	$10,600,000.00	-	-	$2,255,362.64	$23,000,000.00	$66,580,000.00
A11 Foundations	m2	1,451.17	6555.4	3192	1055	2704	1708	272.39	1332	2,655.00	1309	4357
A21 Lowest Floor Construction	m2	1,451.17	6555.4	3192	1055	2704	1708	80.83	1332	2,655.00	1440	4357
A22 Upper Floor Construction	m2	1,366.64	7006	7597	4220	10464	3543	4740.28	3671	6,317.00	3635	11187
A23 Roof Construction	m2	1,453.04	4286.1	1164	1055	2699	1388	2394.58	1349	2,356.00	1854	3387
A31 Walls Below Grade	m2	588.45	447.1	832	798	529	664	54.26	1961	0	1877	2497
A32 Walls Above Grade	m2	2237.56	6055 8	3311	2020	3609	3154	3188.65	2142	17,913.00	6901	9564
B11 Partitions	m2	2,580.13	9363 3	1044	3013	14875	4894	3935.37	2139	10,564.00	2544	21434
Whole Building	m2	2,817.81	13,561.40	10,788.81	5,275.00	13,168.00	5,251.00	4,821.11	5,002.55	8,972.00	5,074.80	15,544.00

Annex J – UBC Academic Building Benchmarks

Figure 10: Percentage Difference from Baseline



Annex K – Total Bill of Materials of UBC Academic Buildings

Table 14: Total Bill of Materials for all UBC Academic Buildings

Material	Mass Value	Mass Unit
#15 Organic Felt	148.17	Tonnes
1/2" Gypsum Fibre Gypsum Board	100.36	Tonnes
1/2" Moisture Resistant Gypsum Board	95.41	Tonnes
1/2" Regular Gypsum Board	1,047.97	Tonnes
3 mil Polyethylene	1.05	Tonnes
5/8" Fire-Rated Type X Gypsum Board	341.17	Tonnes
5/8" Gypsum Fibre Gypsum Board	0.31	Tonnes
5/8" Moisture Resistant Gypsum Board	205.14	Tonnes
5/8" Regular Gypsum Board	1,073.85	Tonnes
6 mil Polyethylene	14.10	Tonnes
8" Concrete Block	11,856.07	Tonnes
Air Barrier	0.17	Tonnes
Aluminum	223.23	Tonnes
Aluminum Clad Wood Window Frame	2.28	Tonnes
Aluminum Window Frame	55.47	Tonnes
Ballast (aggregate stone)	4,552.78	Tonnes
Blown Cellulose	4.84	Tonnes
Cedar Wood Bevel Siding	2.27	Tonnes
Cedar Wood Shiplap Siding	165.00	Tonnes
Cold Rolled Sheet	8.38	Tonnes
Concrete 20 MPa (flyash 35%)	2,583.84	Tonnes
Concrete 20 MPa (flyash av)	74,681.75	Tonnes
Concrete 30 MPa (flyash 25%)	11,081.11	Tonnes
Concrete 30 MPa (flyash 35%)	4,563.98	Tonnes
Concrete 30 MPa (flyash av)	121,065.90	Tonnes
Concrete 60 MPa (flyash av)	691.94	Tonnes
Concrete Brick	1,852.19	Tonnes
Concrete Tile	0.00	Tonnes
Double Glazed Hard Coated Air	33.75	Tonnes
Double Glazed Hard Coated Argon	0.00	Tonnes
Double Glazed No Coating Air	353.73	Tonnes
Double Glazed Soft Coated Argon	10.95	Tonnes
EPDM membrane (black, 60 mil)	8.56	Tonnes
Expanded Polystyrene	27.76	Tonnes
Extruded Polystyrene	127.50	Tonnes
FG Batt R11-15	58.53	Tonnes
FG Batt R20	0.51	Tonnes

Fiber Cement	13.76	Tonnes
Galvanized Decking	88.84	Tonnes
Galvanized Sheet	257.36	Tonnes
Galvanized Studs	459.97	Tonnes
Glass Facer	1.45	Tonnes
Glazing Panel	1,013.87	Tonnes
GluLam Sections	331.84	Tonnes
Hollow Structural Steel	73.46	Tonnes
Joint Compound	277.52	Tonnes
Laminated Veneer Lumber	168.66	Tonnes
Large Dimension Softwood Lumber, kiln-dried	159.73	Tonnes
MBS Metal Roof Cladding - Commercial (26 Ga.)	20.58	Tonnes
MBS Metal Wall Cladding - Commercial (24 Ga.)	0.00	Tonnes
MDI resin	0.00	Tonnes
Metal Wall Cladding - Commercial (26 Ga.)	28.29	Tonnes
Metal Wall Cladding - Residential (30 Ga.)	0.66	Tonnes
Metric Modular (Modular) Brick	3,149.58	Tonnes
Modified Bitumen membrane	336.06	Tonnes
Mortar	13,550.34	Tonnes
MW Batt R11-15	65.43	Tonnes
Nails	42.02	Tonnes
Natural Stone	59.10	Tonnes
Ontario (Standard) Brick	783.25	Tonnes
Open Web Joists	83.25	Tonnes
Oriented Strand Board	32.32	Tonnes
Paper Tape	3.18	Tonnes
Parallel Strand Lumber	154.10	Tonnes
Polyethylene Filter Fabric	1.81	Tonnes
Polyiso Foam Board (unfaced)	41.75	Tonnes
Precast Concrete	16,423.73	Tonnes
PVC Membrane 48 mil	0.00	Tonnes
Rebar, Rod, Light Sections	8,396.01	Tonnes
Roofing Asphalt	755.62	Tonnes
Screws Nuts & Bolts	27.52	Tonnes
Small Dimension Softwood Lumber, kiln-dried	389.13	Tonnes
Softwood Plywood	83.71	Tonnes
Solvent Based Alkyd Paint	0.82	Tonnes
Solvent Based Varnish	0.03	Tonnes
Spandrel Panel	30.72	Tonnes
Stucco over metal mesh	153.32	Tonnes
Stucco over porous surface	567.27	Tonnes
Type III Glass Felt	107.15	Tonnes

Unclad Wood Window Frame	21.88	Tonnes
Vinyl Siding	0.81	Tonnes
Water Based Latex Paint	25.53	Tonnes
Welded Wire Mesh / Ladder Wire	135.03	Tonnes
Wide Flange Sections	7.59	Tonnes

Annex L – Sensitivity Analysis Results

Table 15: Sensitivity Analysis Results

Flyash av to Flyash 35%				
Impact Categories	**Units**	**Baseline**	**Proposed**	**% Difference**
Global Warming Potential	kg CO2 eq	101.60	97.65	-3.9%
Acidification Potential	kg SO2 eq	0.77	0.74	-3.1%
HH Particulate	kg PM2.5 eq	0.39	0.38	-1.9%
Eutrophication Potential	kg N eq	0.44	0.44	-0.2%
Ozone Depletion Potential	kg CFC-11 eq	4.58E-07	0.00	-5.4%
Smog Potential	kg O3 eq	17.57	17.08	-2.8%
Total Primary Energy	MJ	2,134.47	2,115.16	-0.9%
Non-Renewable Energy	MJ	1,786.04	1,769.34	-0.9%
Fossil Fuel Consumption	MJ	1,752.75	1,735.66	-1.0%

Stud Spacing 16 oc to 24 oc				
Impact Categories	**Units**	**Baseline**	**Proposed**	**% Difference**
Global Warming Potential	kg CO2 eq	101.60	100.86	-0.7%
Acidification Potential	kg SO2 eq	0.77	0.76	-1.1%
HH Particulate	kg PM2.5 eq	0.39	0.39	-0.5%
Eutrophication Potential	kg N eq	0.44	0.44	-0.2%
Ozone Depletion Potential	kg CFC-11 eq	4.58E-07	0.00	0.0%
Smog Potential	kg O3 eq	17.57	17.31	-1.5%
Total Primary Energy	MJ	2,134.47	2,117.43	-0.8%
Non-Renewable Energy	MJ	1,786.04	1,775.91	-0.6%
Fossil Fuel Consumption	MJ	1,752.75	1,743.28	-0.5%

Concrete 30MPa to 60 Mpa				
Impact Categories	**Units**	**Baseline**	**Proposed**	**% Difference**
Global Warming Potential	kg CO2 eq	101.60	103.61	2.0%
Acidification Potential	kg SO2 eq	0.77	0.78	1.6%
HH Particulate	kg PM2.5 eq	0.39	0.39	1.0%
Eutrophication Potential	kg N eq	0.44	0.44	0.1%
Ozone Depletion Potential	kg CFC-11 eq	4.58E-07	0.00	2.6%
Smog Potential	kg O3 eq	17.57	17.83	1.5%
Total Primary Energy	MJ	2,134.47	2,147.50	0.6%
Non-Renewable Energy	MJ	1,786.04	1,797.86	0.7%
Fossil Fuel Consumption	MJ	1,752.75	1,764.16	0.7%