LIFE CYCLE ASSESSMENT OF THE FOREST SCIENCE CENTER

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University of British Columbia

CIVL 498C

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PROVISIO

This study has been completed by undergraduate students as part of their coursework at the University of British Columbia (UBC) and is also a contribution to a larger effort – the UBC LCA Project – which aims to support the development of the field of life cycle assessment (LCA).

The information and findings contained in this report have not been through a full critical review and should be considered preliminary.

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Completed November 18th, 2013 as part of a continuing study, the UBC LCA Project

Executive Summary

This study used Life Cycle Assessment (LCA) to assess the environmental performance of the University of British Columbia's Forest Science Centre. The LCA was part of a larger continuing project that seeks to quantify the environmental performance of the buildings at UBC. A previous model of the FSC was reviewed, improved, and reclassified to fit the Canadian Institute of Quantity Surveyors' classification format in order to promote integration of LCA into the existing template used during building design for cost management.

Architectural and structural drawings of the building were coupled with the software programs Athena Impact Estimator for Buildings and Onscreen Takeoff to model the potential impacts created through the production and construction of the building. The material and energy flows from these systems were characterized with the TRACI impact assessment methodology to produce a comprehensive evaluation of the potential environmental impacts.

The greatest environmental impacts were discerned to occur from the suspended concrete slabs that form the upper floors of the building. The results of all studies were used to create a benchmark against which buildings could be evaluated. The FSC was found to have a lower impact than the benchmark in 6 of the 7 impact categories, though the range varied considerably.

Recommendations are proposed to further operationalize LCA at UBC. They include an expansion of the system boundary to cover the operation and maintenance of buildings, and the normalization of impact categories to reflect the sustainable development policies pursued by UBC. Aspects of the building requiring further analysis are also identified so that the study may be improved by future students.

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1.0 General Information on the Assessment

Purpose of the assessment

Life Cycle Assessment (LCA) is a method of quantifying the environmental performance of a product throughout its life cycle by characterizing the material and energy flows entering and exiting a product system by their potential environmental impact.[1] This LCA of an institutional building was completed as a requirement of CIVL 498C and is intended to provide a reference base for the evaluation of environmental impacts from buildings. The intended audience is those involved in development at UBC, including the UBC Sustainability Office given their mandate to promote green building construction[2], and the UBC Board of Governors due to their policy of sustainable development[3], as well as future students of CIVL 498C. It is intended for comparative assertions but only by serving as a benchmark by which the future performance of buildings can be measured, specifically institutional buildings at UBC. Despite a strong commitment to be as accurate as possible, the magnitude and timeframe of the project nonetheless necessitated several assumptions that should be considered during interpretation of results.

Identification of building

The Forest Sciences Centre (FSC) is located at 2424 Main Mall at Agronomy Rd, Vancouver. Designed by Dalla-Lanna/Griffin Architects and built in 1998 at a cost of $47 million ($66.58 million in 2012 dollars), the building contains 2 lecture theaters, 11 classrooms, 230 offices, 36 labs, 25 mechanical and electrical rooms, as well as several storage rooms and washrooms.[4] Massive parallam beams and columns and the extensive use of wood for the interior finishing were included to advertise the use of wood construction materials and add to the ambiance of the building. An important feature is the L-shaped atrium that defines the entrance and study area, while each additional floor hosts a faculty department: Forest Resources Management on the second floor, Forest and Conservation Science on the third, the department of Wood Science on the fourth floor. Joined to the

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[1] (O'Connor & Meil, 2012)
[2] (UBC, 2013)
[3] (UBC, 2005)
[4] (UBC Library, 2008)

building is the Center for Advanced Wood Products, which was not included in this assessment.

Table 1: Details of Assessment

Client for Assessment	Completed as coursework in Civil Engineering technical elective course at the University of British Columbia.
Name and qualification of the assessor	Ian Eddy, B. Sc. Michael Morris and Chu Lin are contributing authors
Impact Assessment method	TRACI v. 2.1
Point of Assessment	15 years
Period of Validity	5 years
Date of Assessment	Completed in December 2013.
Verifier	Student work, study not verified.

2.0 General Information on the Object of Assessment

Functional Equivalent

Functional units are the quantified performance of a product system and are used as a reference unit.[5] Functional units allow for comparisons of the inventory analysis and impact assessment between equivalent product systems.[6] A critical requirement of the ISO standards for Life Cycle Assessment is that product systems must be functionally equivalent for comparisons to be valid, meaning each system should be defined so that an equal amount of product or service is used for the basis of comparison. In terms of building life cycle assessments, the FSC should only be compared against functionally equivalent buildings (Table 2). While the functional unit of the entire building was square meters of floor space, separate functional units were used at the level of the individual CIQS building elements (Table 3).

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[5] (ISO, 2006)

[6] (ISO, 2006b)

Table 2: Characteristics of the object of assessment

Aspect of Object of Assessment	Description
Building Type	Institutional
Technical and functional requirements	Lecture theaters, classrooms, conference rooms, restaurant, offices, and study are
Pattern of use	Weekday use 07:00-18:00 with weekend-use by Forestry students
Required service life	Assumed to be 60 years

Reference Study Period

While life cycle assessments of buildings should include the required service life of the building and the end-of-life in the system boundary[7], the system boundary of this LCA was cradle-to-gate, meaning only the production and construction stages were modelled. This was to preserve the accuracy of the assessment; the modelling was derived almost entirely from structural and architectural drawings that provided little information relevant to the building's operational and end-of-life impacts. In addition, the Impact Estimator does not currently have the capability to model these stages beyond general assumptions that are based on the service life and location of the building.[8] In order to circumvent these assumptions, the reference study period deviated from EN 15978 by assuming a service life of 1 year. However, the assumed service life of the FSC is actually 60 years.

Object of Assessment Scope

The lowest floor of the FSC is the basement, hosting several research labs and a storage space. Supporting the basement are several concrete footings and pads. An intermediate basement is also formed by a split level lecture theater capable of hosting over 300 people. The ground floor is the site of the large L-shaped atrium, as well as several classrooms and the Tim Horton's restaurant. An expansive atrium skylight is supported by parallam beams and columns that span the ground to the ceiling. The second, third and fourth floors contain research labs, department offices, and conference rooms, and each has a concrete bridge spanning the atrium. The second floor also hosts a student study area sheltered by a curved

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[7] (EN 15978, 2010)

[8] (ASMI, 2013a)

curtain wall. The interior walls are steel studded, with a wood veneer on those surrounding the atrium, while the exterior walls are cast in place concrete with brick cladding. Concrete arches stand outside the southeast and southwest entrances. Enclosing the skylight is a concrete and steel roof.

The black box structure, rigidity, and limited data availability of the Athena LCI databases restricts the inclusion of materials beyond the structure and envelope of the building. Consequently the assessment was again forced to deviate from EN 15978 in the interest of maintaining an accurate assessment. In order to complement the CIQS elements used for costing, a modified version of the CIQS level 3 elements was adopted to classify the inputs (Table 3). The functional units were calculated as follows: A11 and A21 – the total area of the slab-on-grade; A22 – total area of all upper floors; A23 – total area of the roof(s); A31 – total area of the walls below grade; A32- total area of the walls above grade; A33- total area of the interior walls.

Table 3: Modified CIQS Level 3 Elements used to classify inputs

CIVL 498C Level 3 Elements		Description	Quantity (Amount)	Units
A11	Foundations	Strip and spread footings & concrete pads	4357	m^2
A21	Lowest Floor Construction	150 mm concrete slab on grade	4357	m^2
A22	Upper Floor Construction	Suspended concrete slabs with supporting columns and staircases	11187	m^2
A23	Roof Construction	Steel, concrete, and skylight roofs with supporting columns and beams	3387	m^2
A31	Walls Below Grade	Cast-in-place concrete walls	2497	m^2
A32	Walls Above Grade	Cast-in-place concrete walls	9564	m^2
B11	Partitions	Steel stud walls with gypsum sideboard	21434	m^2

3.0 Statement of Boundaries and Scenarios Used in the Assessment

System Boundary

The system boundary of the assessment included only two life cycle modules, production and construction. During production, raw materials are extracted, transported to the production site, and manufactured into construction materials. In the construction module, the products are transported to the construction site and used in building construction. Both modules may also include ancillary materials and waste management processes that may not be reflected in the final Bill of Materials, for example the production and disposal of plastic wrapping. The Use and Demolition modules were excluded due to a lack of data and time constraints. However, the consequences of this exclusion must be considered during the interpretation of the results, as the impacts from the operation of a building are typically significantly larger than the other modules.[9]

Production Stage

Process information in the production stage is obtained from the US LCI and Athena LCI databases. When a material is specified in the Impact Estimator, the material's LCI profile is selected from the Athena LCI database. The profile contains data regarding the raw materials and energy used to create the product, the waste generated from its production, and the packaging materials and other ancillary materials used, collected from surveys of manufacturers in accordance with ISO 14040 standards and continuously updated to remain representative of current building practices.[10] The Impact Estimator uses the location of the building to estimate modes of transportation, distance traveled, and the likely supplier of each material. Although Athena conducts market share analyses to determine the origin of products for each region, all products are nonetheless assumed to originate from North America. This assumption is likely correct for some materials (e.g. concrete) but question for others (e.g steel).

Construction stage

Process information in the construction stage is handled similarly to the production stage.

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[9] (Bayer, Gamble, Gentry, & Joshi, 2010)
[10] (ASMI, 2013a)

Again, the Impact Estimator uses the specified location of the building to make several assumptions. For example, the average number of days below freezing is used to determine whether concrete will require additional heating for curing, while the regional emissions profile is used when estimating impacts from grid electricity use. The Impact Estimator also makes several ‘unseen’ assumptions, such as a 5% addition to the known volume of concrete to account for onsite waste.[11] Throughout the entire LCA, the unit process impacts are not distinguishable, as the database is proprietary to the Athena Sustainable Materials Institute. Instead, all impacts are aggregated, separated only by module and whether the impacts originate from transportation.

4.0 Environmental Data

Data Sources

The Athena LCI database was used for material process data, while LCI data for electricity generation and transportation was provided by the US LCI database. The Athena LCI database is a private database administered by the Athena Sustainable Materials Institute. The database is of high quality and regionally sensitive, compiled from over 150 process based LCI and LCA studies**.** It is continuously updated, with the oldest data of 1997 vintage. The US LCI Database is a public and private research partnership that was developed to provide transparent and publicly available LCI data representative of North America. It was created in 2001 and is owned and updated by the National Renewable Energy Library, with regular contributions from the Athena Institute.[12]

Data Adjustments and Substitutions

One material inaccuracy found in the Impact Estimator model is the use of 20 MPa concrete in the slab-on-grade as opposed to the actual 25 MPa. In the absence of reliable 25 MPa LCI data, the average of the LCIA results for 20 and 30 MPa concrete was used. For the LCIA results of the A21 Lowest Floor element, this led to a 1-6% increase across all impact

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[11] (ASMI, 2013a)
[12] (Trusty & Deru, 2005)

categories from the original 20 MPa, but the increase was insignificant for the building as a whole. In calculating the bill of materials, the original 20 MPa concrete was used.

Data Quality

No LCA is without uncertainty. This uncertainty may be defined in several ways, including but not limited to the following:

- Data uncertainty, including uncertainty over inaccurate or missing inventory analysis data as well as the manner in which the data was collected or allocated. Data uncertainty with the impact assessment methodology comprises uncertainty over the fate and dispersion or travel potential of substances. Examples of data uncertainty in the study include the 25 MPa concrete used in the building that was modelled as 20 or 30 MPa.
- Model uncertainty represents uncertainty of the characterization factors used by the impact assessment methodology and also the nature of the relationships of the inventory data. LCA typically assumes linear relationships exist between inputs and outputs to the product system, though economies of scale contradict this assumption. Many characterization factors undergo constant revision as new information becomes available. An example of model uncertainty from the study is the characterization factors used for global warming potential, which are under constant revision.[13]
- Uncertainty due to temporal variability represents uncertainty over data vintage, seasonal effects on emissions and impacts, and how impacts are interpreted over time. Data vintage is particularly a problem with buildings given their long lifetimes. Production and construction processes are constantly evolving and therefore the processes that are modeled may not be accurate for the time at which the building was constructed. Seasonal conditions may affect the inventory analysis in several ways, including the addition of products necessary to protect materials from the elements. The same seasonal conditions have a consequence on the fate and dispersion of substances, e.g. rainy conditions may reduce respiratory exposure to

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[13] (Shine, 2009)

particulate matter. An example of temporal variability from this study is the concrete used during the building construction in 1998 may not be representative of the steel production data used by the Athena LCI, which has been updated partially to reflect significant changes in the technology and relative contribution of operations that occurred in British Columbia since 1998. [14]

- Uncertainty due to spatial variability is the uncertainty over regional differences that may exist in environmental sensitivity (e.g. air pollution is strongly influenced by local geography), the spatial variation of the emissions, and the regional differences that may exist between factories. An example of uncertainty due to spatial variability is the Impact Estimator automatically models seismic conditions in Seattle to the structural calculations for the building despite its location in Vancouver.[15]
- Variability between sources refers to the uncertainty that exists due to the source of LCI data, which may be an average of several factories or even technologies and therefore only an approximation of the actual processes used. It also includes uncertainty over the different human exposure patterns to substances. An example from the study is again concrete, which can be produced using several different kiln technologies.[16]

The location of the building in Vancouver (one of the cities modeled by the Impact Estimator) and its relatively recent construction in 1998 greatly reduces the spatial and temporal uncertainty. Data uncertainty was occasionally an issue, as some envelope materials could not be included (e.g. plywood veneer), but the issues of uncertainty encountered within the assessment generally stemmed from the software and interpretation of the drawings, not the inventory data.

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[14] (ASMI, 2005)
[15] (ASMI, 2013)
[16] (ASMI, 2005)

5.0 List of Indicators Used for Assessment and Expression of Results

The study used the TRACI impact assessment methodology developed by the US EPA.[17] TRACI uses 12 impact categories, with characterization factors representative of the United States developed at the midpoint level. However, only 8 of the 12 impact categories are used in the Impact Estimator: global warming potential, acidification potential, human health particulates, fossil fuel consumption, eutrophication potential, ozone depletion potential, smog formation potential, and total primary energy consumption. A brief description of the impact categories is provided below

Acidification potential (AP): An impact category that is more locally relevant than globally, acidification potential refers to the potential of a substance to acidify the air or water and uses equivalent ions of hydrogen (H^+) as the category indicator. Possible endpoint impacts include soil and vegetation damage and building corrosion.

Eutrophication potential (EP): this impact category refers to the ability of a substance to fertilize a water body, creating excessive plant growth that leads to oxygen depletion during the decomposition of the plant matter. The category indicator is mass of nitrogen (N) equivalents and a possible endpoint impact is loss of biodiversity.

Fossil Fuel Consumption (FFC): fossil fuel consumption uses megajoules (MJ) as the category indicator and includes all non-renewable energy used directly or indirectly in the modelled processes. A possible endpoint impact is increased costs of fossil fuels.

Global Warming Potential (GWP): this impact category measures the `greenhouse` potential of a substance, or its ability to trap heat in the atmosphere. It can be expressed with multiple time horizons; TRACI uses the 100-year time horizon. It is measured in mass equivalents of carbon dioxide (CO_2) and a possible endpoint impact is sea level rise.

Human Health Criteria Air Particulate (HHP): this impact category measures the fine particulate matter that is emitted throughout a product`s life cycle and their potential inhalation. Different sizes of particulates are associated with different respiratory problems.

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[17] (Bare, 2002)

The Athena IE uses equivalents of PM_{10} as the category indicator. Disability Adjusted Life Years are a potential endpoint impact.

Ozone Depletion Potential (ODP): This impact category accounts for impacts resulting in a reduction of the ozone layer within the stratosphere. The ozone layer shields the earth from ultraviolet radiation emitted by the sun. The impact category uses mass equivalents of trichlorofluoromethane (CFC-11) as the impact indicator and a possible endpoint is disability adjusted life years.

Smog Potential (SP): This impact category occurs at a local scale and includes substances that, when trapped near ground level, result in the formation of smog. Smog can have several human health consequences, thus a possible endpoint impact is disability adjusted life years. The Smog Potential impact category uses the impact indicator mass equivalents of ozone (O_3).

6.0 Model Development

Generally, each level 3 element was modeled according to the same approach. The OnScreen Takeoffs of the drawings from the 2009 model were reviewed and verified to be consistent with the 2009 Impact Estimator inputs. If differences were found, the corresponding input was located in the Inputs and Assumptions document to determine if the difference was due to a modelling issue in Athena (e.g. a maximum floor span necessitated certain manipulation of the inputs) or an error (e.g. the Excel inputs document was not consistent with the Athena inputs), in which case the appropriate document was corrected. Several of the original Impact Estimator inputs did not have takeoffs and were estimated by the authors. However as no basis was provided to show how the figures were arrived at, thus they were recalculated. Lastly, the 2009 and 2010 Excel inputs documents were compared, though without the 2010 takeoffs this was not as useful a strategy as it might have otherwise been. This resulted in an updated 2013 Excel Inputs document (Annex D). Effort was focused on improving the take offs in addition to the model in order to make the entire LCA more transparent for future use.

Some of the CIQS elements had distinct issues associated with their modeling (Annex D). The parallam columns and beams included in the A23 Roof element lacked takeoffs and therefore the height and width of one column was estimated with OnScreen Takeoff as well as analog measurement and multiplied by the number of beams. The crossbeams were estimated in the same manner. The skylight was modeled as a curtain roof as no skylight option currently exists in the Impact Estimator. The concrete columns were divided according to the takeoffs to separate the length of column supporting the roof from the columns supporting the floors. The original dimensions of the columns remained unchanged; this is recognized as an area of improvement for future iterations of the FSC LCA. The supported areas of the various columns are not assumed to be correct, however manipulating them did not significantly affect the results. Lastly, the area of the skylight was modeled twice in the 2009 model, and this redundancy was removed.

Improvements with A32 included adjustments to the dimensions of the curtain walls after the addition of the takeoffs, which were missing from the 2009 drawings. 3 mil polyethylene vapour barriers and Batt fiberglass insulation were added to the concrete walls. The most significant improvement was the recalculation of wall area using linear takeoffs as opposed to area take-offs. The original area takeoffs were limited to the area of wall with brick cladding, underestimating the total area by approximately 20%.

The A22 Upper Floors element was improved through the separation of the floor inputs. Originally all floors were compiled as a single input. However, the 2009 model separated the concrete bridge spanning the atrium throughout floors 2-4 as a separate input. This was not reincorporated into the floor space due to time constraints. The mass of steel required for the staircases was estimated using Lin's 2010 figure but increased by a factor of 1000 to correct for an arithmetic error. This decreased the quantity of galvanized decking from 270 tons to 7.95 tons.

The B11 Partitions element was improved by changing the assembly component from wood to steel studs, adding insulation (Lin's assumption of 89 mm Batt fiberglass was used) and recalculating the number of doors. Adjustments were made to the length of the walls as well. Window area of the steel stud wall was conservatively estimated to be 200 m^2, a tentative figure but an improvement from zero. The other elements were left unchanged from the 2009 model, though in the calculation of the slab-on-grade the area of the ground floor slab resting on grade was subtracted from upper floors and added to the lowest floor element.

Reference flows are defined as the outputs from processes that are required to achieve the functions expressed by a functional unit.[18] In the case of a building, reference flows represent the materials used in the construction of the building. The Impact Estimator automatically generates a list of reference flows based on the specified inputs. Table 4Table 10 list the reference flows for the FSC for each CIQS element. Concrete was typically the largest contributor by mass, except in B11 where plywood used in the steel stud walls was greater.

Table 4: Bill of Materials for A11 Foundations (4357 m^2)

Material	Quantity	Unit
Concrete 30 MPa (flyash av)	4561.074	tonnes
Rebar, Rod, Light Sections	6.628	tonnes

Table 5: Bill of Materials for A21 Lowest Floor (4357 m^2)

Material	Quantity	Unit
Concrete 20 MPa (flyash av)	666.477	tonnes
Concrete 30 MPa (flyash av)	619.379	tonnes
Welded Wire Mesh / Ladder Wire	4.760	tonnes

Table 6: Bill of Materials for A22 Upper Floors (11187 m^2)

Material	Quantity	Unit
Concrete 30 MPa (flyash av)	10054.144	tonnes
Rebar, Rod, Light Sections	386.480	tonnes
Wide Flange Sections	103.194	tonnes
1/2" Regular Gypsum Board	62.836	tonnes

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[18] (ISO, 2006b)

Screws Nuts & Bolts	8.454	tonnes
Galvanized Decking	8.030	tonnes
Joint Compound	7.781	tonnes
Paper Tape	0.089	tonnes
Nails	0.073	tonnes

Table 7: Bill of Materials for A23 Roof Construction (3387 m^2)

Material	Quantity	Unit
Concrete 20 MPa (flyash av)	1625.715	tonnes
Concrete 30 MPa (flyash av)	240.300	tonnes
Ballast (aggregate stone)	209.292	tonnes
Parallel Strand Lumber	89.453	tonnes
Rebar, Rod, Light Sections	79.062	tonnes
Wide Flange Sections	41.600	tonnes
Glazing Panel	29.748	tonnes
Softwood Plywood	29.198	tonnes
Blown Cellulose	29.026	tonnes
Galvanized Decking	16.090	tonnes
Open Web Joists	15.429	tonnes
Aluminum	10.630	tonnes
Small Dimension Softwood Lumber, kiln-dried	5.208	tonnes
PVC Membrane 48 mil	4.989	tonnes
FG Batt R11-15	4.629	tonnes
Screws Nuts & Bolts	3.385	tonnes
Galvanized Sheet	1.394	tonnes
6 mil Polyethylene	0.508	tonnes
Nails	0.395	tonnes
EPDM membrane (black, 60 mil)	0.141	tonnes
3 mil Polyethylene	0.129	tonnes

Table 8: Bill of Materials for A31 Walls Below Grade (2497 m^2)

Material	Quantity	Unit
Concrete 20 MPa (flyash av)	1801.722	tonnes
Concrete Brick	640.515	tonnes
Mortar	66.187	tonnes
Rebar, Rod, Light Sections	22.258	tonnes
FG Batt R11-15	11.801	tonnes
Galvanized Sheet	0.743	tonnes
Cold Rolled Sheet	0.536	tonnes
Nails	0.187	tonnes
Solvent Based Alkyd Paint	0.003	tonnes

Table 9: Bill of Materials for A32 Walls Above Grade (9564 m^2)

Material	Quantity	Unit
Concrete 20 MPa (flyash av)	1635.753	tonnes
Split-faced Concrete Block	1547.810	tonnes
Mortar	366.013	tonnes
Double Glazed Hard Coated Air	60.010	tonnes
Rebar, Rod, Light Sections	24.891	tonnes
Double Glazed No Coating Air	18.905	Tonnes
Aluminum	16.531	tonnes
Glazing Panel	16.157	tonnes
FG Batt R50	10.226	tonnes
Modified Bitumen membrane	6.039	tonnes
FG Batt R11-15	5.081	tonnes
Galvanized Sheet	1.149	tonnes
Nails	0.854	tonnes
EPDM membrane (black, 60 mil)	0.812	tonnes
Cold Rolled Sheet	0.677	tonnes
3 mil Polyethylene	0.267	tonnes
Screws Nuts & Bolts	0.201	tonnes

Table 10: Bill of Materials for B11 Partitions (21,434 m^2)

Material	Quantity	Unit
Softwood Plywood	10473.085	tonnes
Concrete 20 MPa (flyash av)	1337.922	tonnes
Concrete Brick	369.330	tonnes
1/2" Regular Gypsum Board	138.033	tonnes
FG Batt R11-15	77.241	tonnes
Galvanized Studs	66.852	tonnes
Mortar	38.164	tonnes
5/8" Regular Gypsum Board	37.583	tonnes
Double Glazed Hard Coated Air	37.310	tonnes
Galvanized Sheet	33.360	tonnes
Rebar, Rod, Light Sections	29.745	tonnes
Small Dimension Softwood Lumber, kiln-dried	25.194	tonnes
Joint Compound	20.737	tonnes
Aluminum	5.148	tonnes
Nails	2.503	tonnes
Screws Nuts & Bolts	2.073	tonnes
3 mil Polyethylene	1.381	tonnes
EPDM membrane (black, 60 mil)	0.352	tonnes
Cold Rolled Sheet	0.309	tonnes
Paper Tape	0.238	tonnes
Water Based Latex Paint	0.236	tonnes
Solvent Based Alkyd Paint	0.007	tonnes

7.0 Communication of Assessment Results

Life Cycle Results

The LCIA results followed the same general pattern across all impact categories: the A22 Upper Floors element was found to have the greatest potential environmental impacts, followed by the upper floors and roof elements, then the foundation and partition walls, and lastly the walls below grade and slab-on-grade (Figure 1 Figure 2). This trend can be partially predicted by the mass of the reference flows for each element (tables 4-10). However, the HHP and SP impacts did not follow the trend as closely as other impact categories. SP impacts were more strongly influenced by the mass of concrete used in the element than other impact categories, while hotspots in the HHP category were the curtain walls and roof, and the walls with the most windows, likely due to the addition of aluminum. GWP hotspots originated from the inputs with the most concrete. The large parallam columns and beams of the FSC, designed mainly for aesthetic purposes, did not appear to significantly influence the LCIA results.

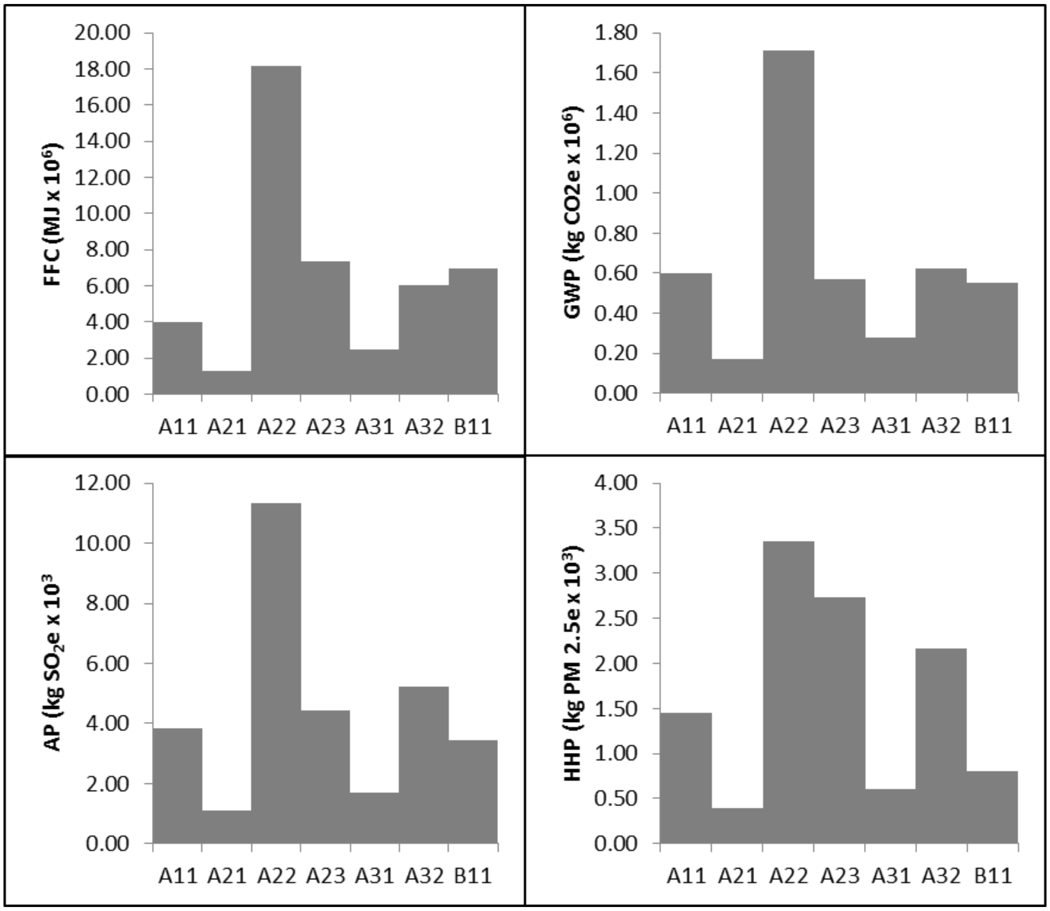

Figure 1: Fossil Fuel Consumption, Global Warming Potential, Acidification Potential, and Human Health Particulate Potential LCIA results by CIQS level 3 element of the FSC.

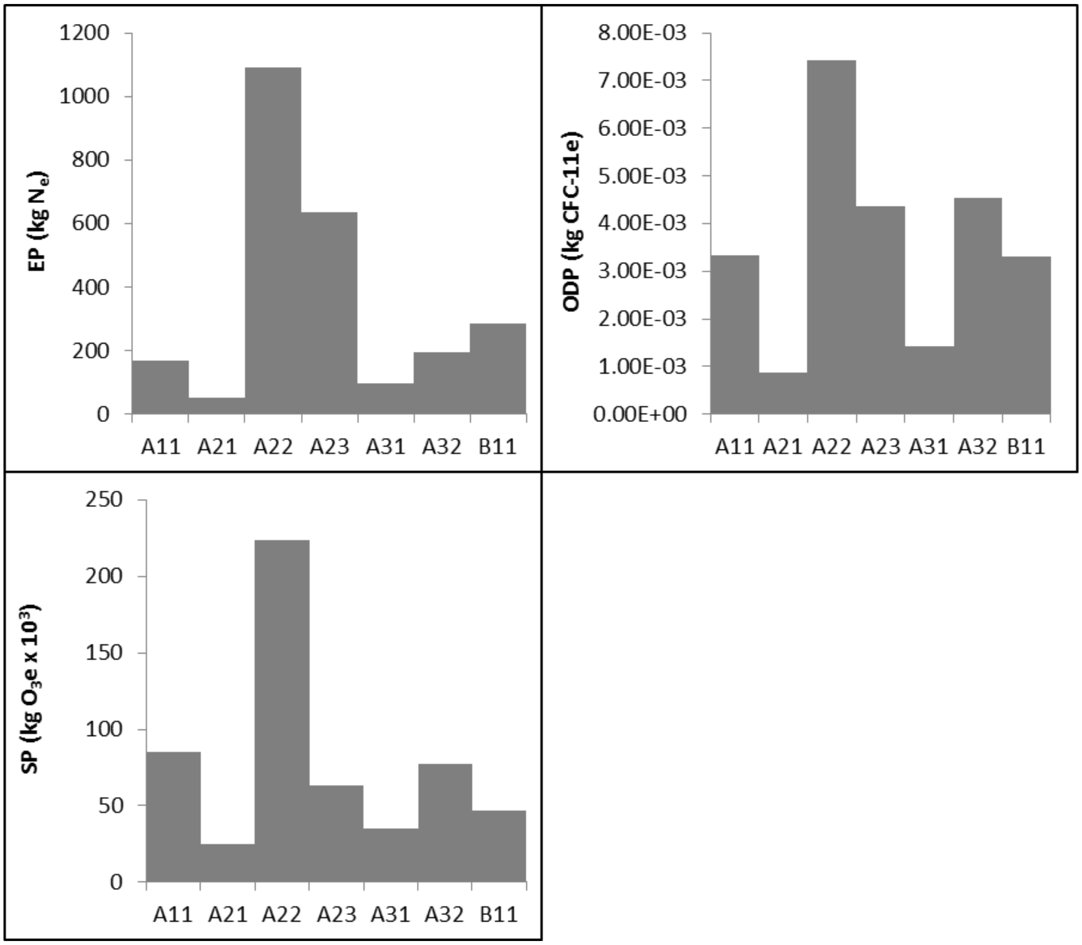

Figure 2: Ozone Depletion Potential, Smog Potential, and Eutrophication Potential LCIA results by CIQS Level 3 elements of the FSC

Annexes A-D of this report are included below in order to add more depth to the interpretation of the results. In Annex A the results of the FSC are evaluated against a benchmark representing the average of all buildings evaluated in the 2013 CIVL 498C class. The age of these buildings spanned a considerable range, from 1 year old in the case of the Pharmacy building to 88 years for the Geography building. However, all buildings were modeled as having been constructed in 2012. The details of the benchmark are further discussed in Annex A. Annex B contains reflection on the implementation of LCA for buildings, as well as how LCA might be more effectively used at UBC. Annex C contains the personal reflections of the author upon the project, intended to add some context for future students who may use this data, while Annex D lists the full Microsoft Excel Inputs and Assumptions document.

Annex A - Interpretation of Assessment Results

Benchmark Development

By comparing the LCI and LCIA results of a building against a benchmark, the building's environmental performance is put in context. Benchmarking also allows for tracking improvements in the LCA results over time. There are several methods of benchmarking, including comparisons between past and present performance, against industry averages, and against the best in the building class.[19] However, as benchmarking entails comparative assertion, it requires buildings to be functionally equivalent. The building and the benchmark must share a common goal and scope, given the considerable influence that the various components of the goal and scope have on assessment results (system boundaries, assumptions, impact assessment methodologies, etc.) This assessment compared the performance of the FSC against a benchmark representing the average of all the buildings assessed at UBC. While it is difficult to establish complete functional equivalence in the building industry[20], the benchmark includes only institutional buildings (no residential buildings were included), modeled using the same general methodology, and is sufficiently similar to allow for some basic assertions.

UBC Academic Building Benchmark

The FSC performed strongly in comparison with the benchmark, with the building as a whole between 65-80% of the benchmark impact score across all impact categories except ODP (Figure 3). At the scale of the level 3 CIQS element, the LCIA results were less consistent (Figure 4). Partition walls and upper floors were found to have significantly less of an impact in every category, a decrease of ~35% for the upper floors and ~75% for the partitions. A31 Walls Below Grade was the only element to have a greater impact than the benchmark in every impact category. The foundation and lowest floor were very similar to the benchmark, while the LCIA results for the upper floors and roof were mixed. Further analysis is required to identify the exact materials responsible for the greater ODP impact of the FSC; however it is hypothesized by the author to be the result of aluminum window

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[19] (Bayer et al., 2010)
[20] (Bayer et al., 2010)

frames. Overall, the FSC LCIA results were unexpectedly low in comparison to the benchmark for two reasons. The considerable use of concrete in the exterior walls of the FSC was expected to result in greater environmental impact scores[21], while the large atrium results in a less efficient floor-to-wall ratio, leading to less overall floor space than might be expected in a similar sized building with no atrium.

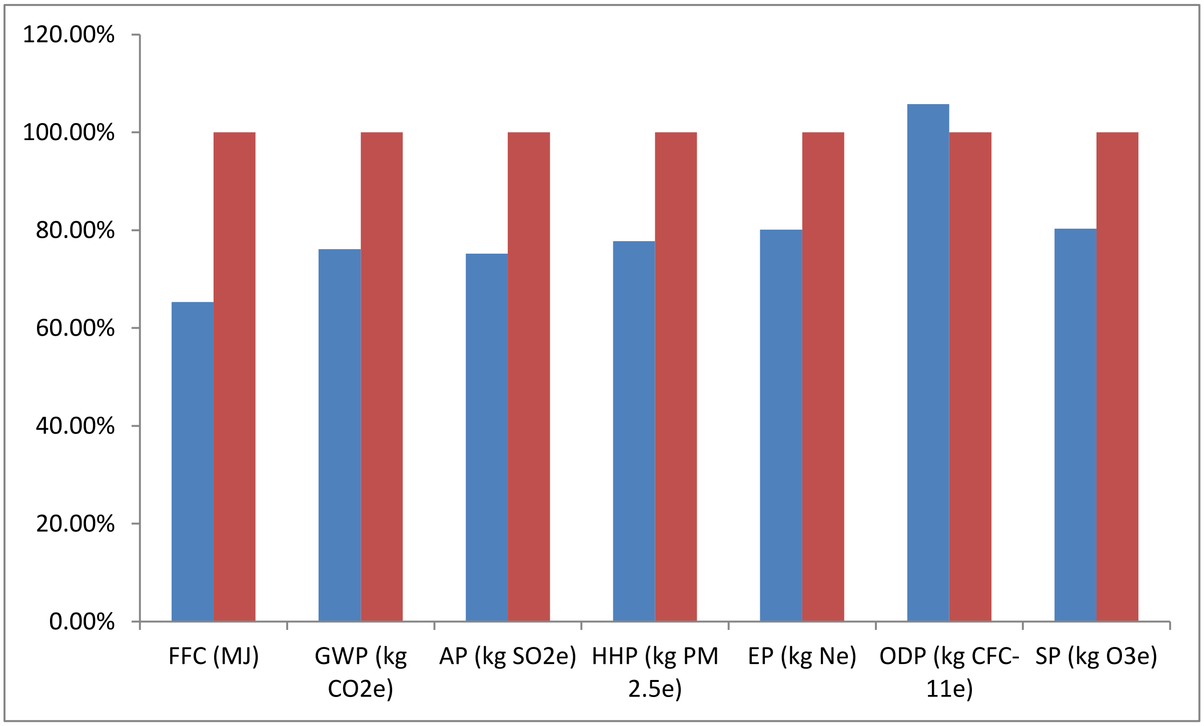

Figure 3: FSC LCIA results against the Oct. 31 2013 benchmark for the entire building.

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[21] (Bayer et al., 2010)

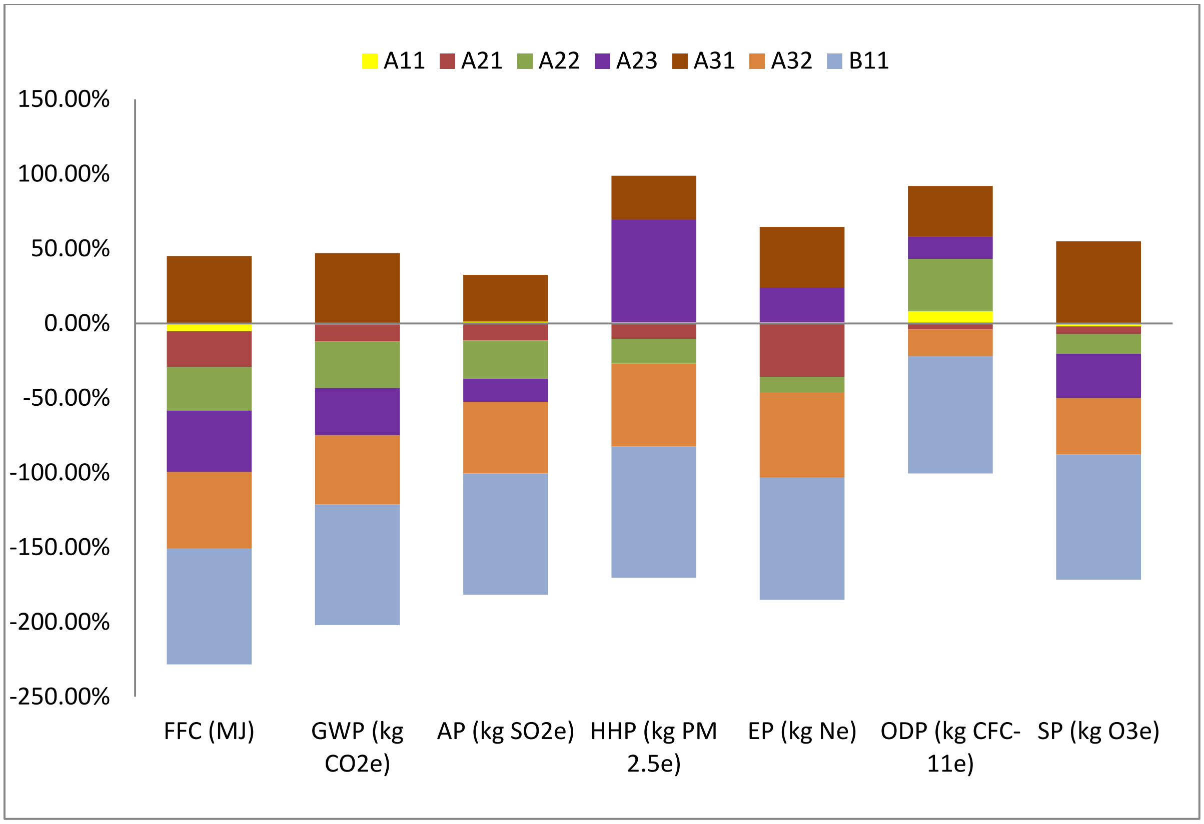

Figure 4: FSC LCIA results as the % difference from the Oct. 31 2013 benchmark by level 3 CIQS element. 0% represents no change from the benchmark.

Global Warming Potential and Cost Comparisons

The construction cost of the buildings, expressed in 2012 $CAD, and their GWP were compared using two methods. First the overall construction costs and GWP of buildings was assessed (Figure 5). This did not control for building size. Additionally, at the time of writing, some of the costs were suspected to have not been converted into 2012 dollars. The new UBC Pharmacy building proved to be a significant outlier, built at a cost of $150 million. For these reasons, the building cost per square meter was compared with the GWP per square meter, while excluding buildings with a cost per square meter not yet converted to 2012 dollars (Figure 6). However, no trend was evident. This is promising, as it suggests that buildings can be built using environmentally friendly materials and methods without an escalation in cost, though the small sample size restricts much extrapolation. Among the buildings studied, the FSC was found to have a greater GWP per square meter, contradicting the earlier findings. This is explained by the different sample size, as only 12 and 8 buildings were included in figures Figure 5Figure 6, respectively.

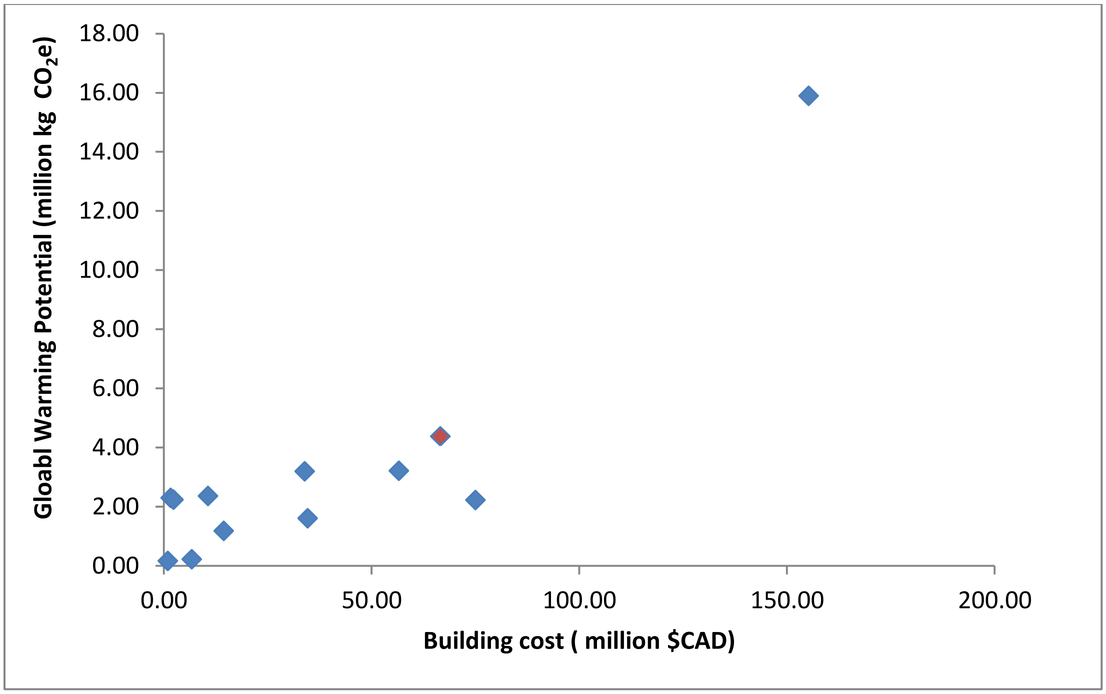

Figure 5: Global warming potential and cost of institutional buildings at UBC. The FSC is shown in red.

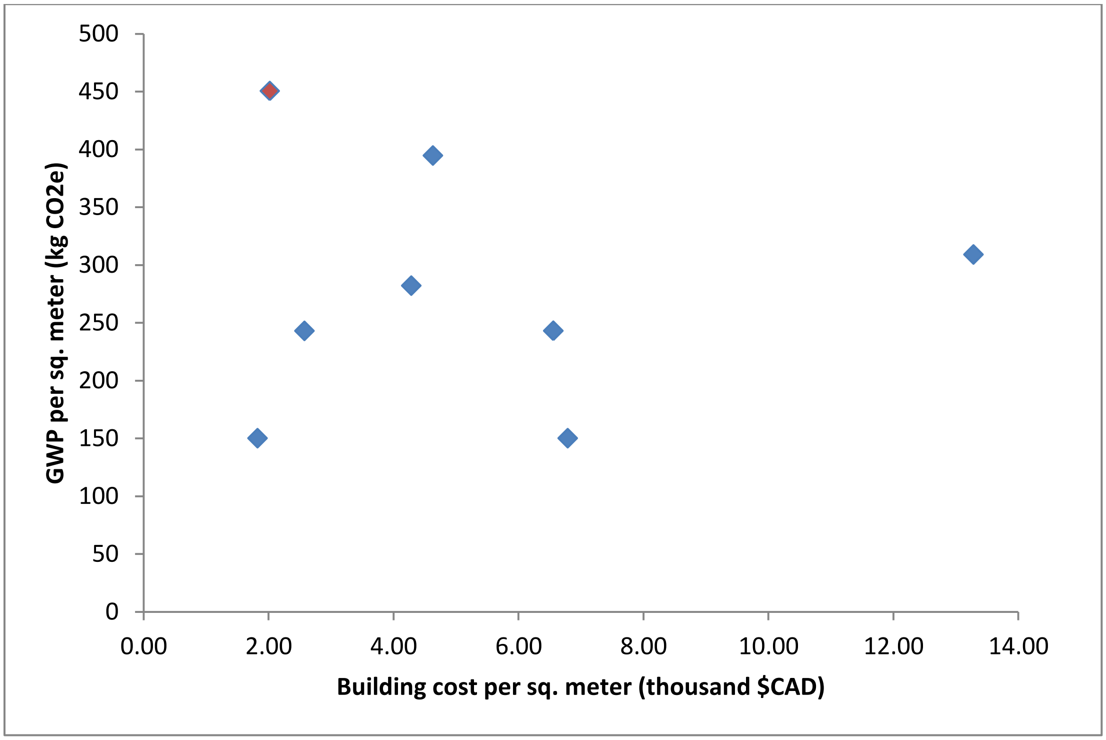

Figure 6: Global warming potential and cost per square meter of institutional building at UBC. The FSC is shown in red.

Annex B - Recommendations for LCA Use

Several considerations are suggested for LCA to achieve its full potential in providing transparent, accurate estimations of the environmental performance of buildings as well as identify where gains are most feasible. First, it is critical that the full life cycle of the building be assessed, beyond the production and construction modules. Not only is the use and maintenance module typically regarded as having a considerably greater impact than other modules,[22] but without its inclusion in the LCA it is impossible to determine whether material substitutions in the production and construction stages actually lead to lesser impacts overall. For example, the addition of an insulating material may lead to greater production and construction impacts, but reduce the energy used for heating and cooling, which can be considerable over the lifetime of a building. The daily, monthly, and yearly energy performance of many buildings at UBC is already known and tracked in real time[23], and could be incorporated into the CIVL 498C project.

Secondly, LCA should be applied during the design stage if it is to be most efficient. A common conception is that the most significant decisions regarding a building's environmental performance are made during the design stage.[24] The initial design of a building determines the baseline from which it begins its operational life[25]. LCA provides the capability to model the construction and operational impacts before any design choices become permanent, ensuring avoidable impacts are kept to a minimum. Retrofitting a building is significantly more costly than initially substituting a different material, therefore development that is both financially and environmentally sustainable begins during building design.

However, both of these suggestions depend upon the underlying assumption of high quality data with minimal uncertainty. This can be especially challenging in the building construction industry; the long lifetimes of buildings add considerable uncertainty to models, as accurately predicting 60 years into the future is difficult. In addition, buildings

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[22] (Bayer et al., 2010)
[23] The University of British Columbia (UBC) and Pulse Energy 2013
[24] (Malin, 2005)
[25] (Scheuer, Keoleian, & Reppe, 2003)

are complex products, utilizing hundreds of materials, each potentially associated with several upstream processes. Regarding the CIVL 498C project, no other buildings exist with exactly the same material properties and environmental conditions as those modeled in the class, making external comparisons difficult. Therefore, more detailed descriptions of the materials than what is often provided in the architectural drawings are needed, while software such as Athena must be either exhaustive in the materials they include or transparent enough to be easily manipulated. Lastly, the results of an LCA must matter to the audience it seeks to reach. There is little value in accurately modeling the smog formation potential of a building if it is of no concern to the builders, owners, or occupants. A survey was conducted in the 2013 CIVL 498C class to examine whether all environmental impacts were of equal concern to the students (they were not) and this is probably indicative of the general population as well. Surveys such as this are necessary for LCA to accurately reflect the notion of sustainable design that is currently sought by so many.

The following suggestions are meant to take this into account in order to improve the application of LCA at UBC:

1) Modeling of the operational and maintenance phase of buildings to achieve more meaningful LCA results, even if at the expense of modeling fewer buildings.

2) More consultation between experienced building designers and LCA practitioners to improve the accuracy of the models.

3) Impact aversion surveys be applied to a larger segment of the UBC population than the CIVL 498C students to better qualify the idea of sustainable development at UBC.

Annex C - Author Reflection

Prior to enrolling in CIVL 498C, I acquired some experience with LCA while working as a Teaching Assistant in CONS 452. I was tasked with compiling an introductory LCA exercise under the supervision of Dr. Paul MacFarlane. The course introduced LCA terminology and explored the topics of uncertainty, comparative life cycle assessments, and limitations of LCA. However, the focus of the case studies was primarily on agricultural products and electricity generation, using more simplistic models in terms of upstream and downstream processes than used in CIVL 498C. In addition this experience, I have a B. Sc. in natural resource conservation, so I am familiar with many of the impact categories used in the course.

My interest in the course stemmed from my desire to solidify my understanding of the finer details of LCA, develop my modelling abilities, and practice with LCA software. I have found knowledge of LCA software is a requisite skill to progress in the field of LCA. It is critical to understand how the vast datasets used in LCA are manipulated and interpreted, and this begins with understanding the software. The largest challenge I faced this course came from my lack of a civil engineering background. While the LCA terminology may have been new to some, I was completely unfamiliar with the building and construction terminology, and the architectural drawings. In addition, I received Excel and Athena Impact Estimator files that corresponded to different building reports for the FSC, and a corrupted OST file; this caused considerable confusion throughout the course.

Table 11: Demonstrated CEAB attributes

	Name	Content Code	Comments on demonstrated CEAB attributes
1	Knowledge Base	A	Though not math intensive, comparing buildings against benchmark and between elements required
2	Problem Analysis	A	The interpretation of complex results was required.
3	Investigation	IDA	Analysis and improvement of previous models was emphasized, as well as interpretation of results.
4	Design	IDA	Though the focus was specifically environmental, the course presented a novel solution for designing sustainable systems.
5	Use of Engineering Tools	IDA	Introduced several software tools and how to manipulate them when dealing with complex data
6	Individual and Team Work	D	The course promoted group and individual work.
7	Communication	D	Guest lectures, class discussions, and presentations were instrumental to the class, developing communicational skills.
8	Professionalism	N/A	N/A
9	Impact of Engineering on Society and the Environment	IDA	The class had a strong focus on sustainable design and environmental stewardship, and introduced many environmental issues. The topic of uncertainty was equally well discussed.
10	Ethics and Equity	N/A	
11	Economics and Project Management	I	Introduced the concept of life cycle costing as well as quantity surveying.
12	Life-long Learning	IDA	Introduced resources for further learning and expounded on advances at the forefront of LCA science

Annex D – Impact Estimator Inputs and Assumptions

Impact Estimator Inputs

Note: the 2009 model inputs were in imperial units and have not all been adjusted to metric.

Element	Quantity	Unit	Assembly Type				
A11 Foundation	4357.01	m2	1.1 Concrete Footing				
				1.1.1 F1			
					Length (ft)	4.592	4.592
					Width (ft)	3.28	3.28
					Thickness (ft)	0.656	0.656
					Concrete (psi)	3600	2900
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	10M	10M
				1.1.2 F2			
					Length (ft)	4.92	24.6
					Width (ft)	4.92	4.92
					Thickness (ft)	1.148	1.148
					Concrete (psi)	3600	2900
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	15M	15M
				1.1.3 F3			
					Length (ft)	7.872	23.616
					Width (ft)	7.872	7.872
					Thickness (ft)	1.476	1.476
					Concrete (psi)	3600	2900
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	20M	20M
				1.1.4 F4			
					Length (ft)	6.56	13.12
					Width (ft)	6.56	6.56
					Thickness (ft)	1.312	1.312
					Concrete (psi)	3600	2900
					Concrete flyash %	AVERAGE	AVERAGE

	Rebar	20M	20M
1.1.5 F5			
	Length (ft)	7.216	21.648
	Width (ft)	7.216	7.216
	Thickness (ft)	1.476	1.476
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	20M	20M
1.1.6 F6			
	Length (ft)	5.576	16.728
	Width (ft)	5.576	5.576
	Thickness (ft)	0.984	0.984
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	20M	20M
1.1.7 F7			
	Length (ft)	5.904	47.232
	Width (ft)	5.904	5.904
	Thickness (ft)	1.312	1.312
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	20M	20M
1.1.8 F8			
	Length (ft)	9.184	110.208
	Width (ft)	9.184	9.184
	Thickness (ft)	1.804	0.902
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M
1.1.9 F9			
	Length (ft)	5.904	41.328
	Width (ft)	6.232	6.232
	Thickness (ft)	1.148	1.148
	Concrete (psi)	3600	2900

	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	20M	20M
1.1.10 F10			
	Length (ft)	5.904	5.904
	Width (ft)	5.904	5.904
	Thickness (ft)	1.148	1.148
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	20M	20M
1.1.11 F11			
	Length (ft)	4.92	78.72
	Width (ft)	4.92	4.92
	Thickness (ft)	1.968	0.984
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	20M	20M
1.1.12 F12			
	Length (ft)	6.888	55.104
	Width (ft)	3.936	3.936
	Thickness (ft)	0.82	0.82
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	10M	10M
1.1.13 F13			
	Length (ft)	3.936	7.872
	Width (ft)	3.936	3.936
	Thickness (ft)	1.312	1.312
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	15M	15M
1.1.14 F14			
	Length (ft)	12.792	12.792
	Width (ft)	5.904	5.904
	Thickness (ft)	1.312	1.312

	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	15M	15M
1.1.15 F15			
	Length (ft)	11.808	23.616
	Width (ft)	3.936	3.936
	Thickness (ft)	2.296	1.148
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	15M	15M
1.1.16 F16			
	Length (ft)	10.168	20.336
	Width (ft)	3.28	3.28
	Thickness (ft)	2.624	1.312
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M
1.1.17 F20			
	Length (ft)	29.52	29.52
	Width (ft)	29.52	29.52
	Thickness (ft)	3.28	3.28
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	20M	20M
1.1.18 F21			
	Length (ft)	39.032	78.064
	Width (ft)	39.032	39.032
	Thickness (ft)	3.28	1.64
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M
1.1.19 F22			
	Length (ft)	22.96	45.92
	Width (ft)	22.96	22.96

	Thickness (ft)	3.28	1.64
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M

1.1.20 F23

	Length (ft)	36.08	72.16
	Width (ft)	19.68	19.68
	Thickness (ft)	2.952	1.476
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M

1.1.21 F24

	Length (ft)	29.192	58.384
	Width (ft)	29.192	29.192
	Thickness (ft)	3.28	1.64
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M

1.1.22 F25

	Length (ft)	132.512	265.024
	Width (ft)	66.256	66.256
	Thickness (ft)	3.28	1.64
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M

1.1.23 F27

	Length (ft)	29.192	58.384
	Width (ft)	29.192	29.192
	Thickness (ft)	3.28	1.64
	Concrete (psi)	3600	2900
	Concrete flyash %	AVERAGE	AVERAGE
	Rebar	25M	20M

1.1.24 F28

Length (ft)	31.16	62.32
Width (ft)	31.16	31.16
Thickness (ft)	3.28	1.64
Concrete (psi)	3600	2900
Concrete flyash %	AVERAGE	AVERAGE
Rebar	25M	20M

1.1.25 F29

Length (ft)	13.12	39.36
Width (ft)	42.64	42.64
Thickness (ft)	3.936	1.312
Concrete (psi)	3600	2900
Concrete flyash %	AVERAGE	AVERAGE
Rebar	25M	20M

1.1.26 F31

Length (ft)	28.864	57.728
Width (ft)	28.864	28.864
Thickness (ft)	3.28	1.64
Concrete (psi)	3600	2900
Concrete flyash %	AVERAGE	AVERAGE
Rebar	25M	20M

1.1.27 F32

Length (ft)	22.96	45.92
Width (ft)	22.96	22.96
Thickness (ft)	3.28	1.64
Concrete (psi)	3600	2900
Concrete flyash %	AVERAGE	AVERAGE
Rebar	25M	20M

1.1.28 F33

Length (ft)	45.92	91.84
Width (ft)	13.12	13.12
Thickness (ft)	3.28	1.64
Concrete (psi)	3600	2900
Concrete flyash %	AVERAGE	AVERAGE

					Rebar	25M	20M
				1.2.29 CF1			
					Length (ft)	7.872	23.616
					Width (ft)	7.872	7.872
					Thickness (ft)	3.936	1.312
					Concrete (psi)	3600	2900
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	25M	20M
				1.2.30 CF2			
					Length (ft)	5.904	11.808
					Width (ft)	2.952	2.952
					Thickness (ft)	2.952	1.476
					Concrete (psi)	3600	2900
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	15M	15M
			1.3 Concrete Strip Footing				
				1.3.1 F30			
					Length (ft)	262.4	262.4
					Width (ft)	6.56	6.56
					Thickness (ft)	1.968	1.968
					Concrete (psi)	3600	3600
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	20M	20M
				1.3.2 SF1			
					Length (ft)	49.2	49.2
					Width (ft)	3.28	3.28
					Thickness (ft)	0.984	0.984
					Concrete (psi)	3600	3600
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	20M	20M
				1.3.3 SF2			
					Length (ft)	557.6	557.6
					Width (ft)	2.296	2.296
					Thickness (ft)	0.984	0.984

					Concrete (psi)	3600	3600
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	15M	15M
				1.3.4 SF3			
					Length (ft)	32.8	32.8
					Width (ft)	3.936	3.936
					Thickness (ft)	0.984	0.984
					Concrete (psi)	3600	3600
					Concrete flyash %	AVERAGE	AVERAGE
					Rebar	20M	20M
			1.4 Slab on Grade Concrete Pad				
				1.4.1 CP1			
					Length (ft)	44.28	44.28
					Width (ft)	44.28	44.28
					Thickness (ft)	0.328	0.328
					Concrete (psi)	3600	3600
					Concrete flyash %	AVERAGE	AVERAGE
A21 Lowest Floor	4357.01	m2	2.1 Slab on Grade				
				2.1.1 Concrete Slab on Grade (basement)			
					Length (m)	42.66	52.25
					Width (m)	42.66	52.25
					Thickness (mm)	150	100
					Concrete (MPa)	25	20
					Concrete flyash %	AVERAGE	AVERAGE
				2.1.2 Concrete Slab on Grade (ground floor)			
					Length (m)	50.37	50.37
					Width (m)	50.37	50.37
					thickness (mm)	100 mm	100 mm
					Concrete (Mpa)	-	30
					Concrete flyash %	Average	Average
A22 Upper Floor Construction	11186.91	m2	3.1 Suspended Concrete Slabs				
				3.1.1 FL1			
					Width (m)	42.66	186.67
					Length (m)	42.66	9.75

					Concrete (MPa)	-	30
					Concrete flyash %	-	average
					Live Load	-	2.4 kPa
					Category	-	Gypsum board
					Type	-	regular 1/2''
				3.1.2 FL2			
					Width (m)	57.741	341.95
					Length (m)	57.741	9.75
					Concrete (MPa)	-	30
					Concrete flyash %	-	average
					Live Load	-	2.4 kPa
					Category	-	Gypsum board
					Type	-	regular 1/2''
				3.1.3 FL3			
					Width (m)	54.5	304.82
					Length (m)	54.5	9.75
					Concrete (MPa)	-	30
					Concrete flyash %	-	average
					Live Load	-	2.4 kPa
					Category	-	Gypsum board
					Type	-	regular 1/2''
				3.1.4 FL4			
					Width (m)	50.872	265.43
					Length (m)	50.872	9.75
					Concrete (MPa)	-	30
					Concrete flyash %	-	average
					Live Load	-	2.4 kPa
					Category	-	Gypsum board
					Type	-	regular 1/2''
				3.1.5 Bridge			
					Width (m)	21.79	51.96
					Length (m)	21.79	9.144

					Concrete (MPa)	3600	3600
					Concrete flyash %	-	average
					Category	-	Gypsum board
					Type	-	Regular 1/2"
			3.2 Extra Materials				
				3.2.1 Galvanized decking			
					Steel Staircase (Tons)	-	7.95
			3.3 Concrete Column/Beams				
				3.3.1 C1			
					Number of bays per row	8	8
					Number of rows	2	2
					Floor to floor height (ft)	13.94	13.94
					Bay sizes (ft)	14.76	14.76
					Supported span (ft)	19.68	19.68
					Live load (psi)	0.7	0.7
				3.3.2 C2			
					Number of bays per row	9	9
					Number of rows	3	3
					Floor to floor height (ft)	21.4512	21.4512
					Bay sizes (ft)	10.824	10.824
					Supported span (ft)	27.88	27.88
					Live load (psi)	0.7	0.7
				3.3.3 C3			
					Number of bays per row	7	7
					Number of rows	1	1
					Floor to floor height (ft)	7.9376	7.9376
					Bay sizes (ft)	17.056	17.056

					Supported span (ft)	25.584	25.584
					Live load (psi)	0.7	0.7
				3.3.4 C4			
					Number of bays per row	12	12
					Number of rows	13	13
					Floor to floor height (ft)	31.242	31.242
					Bay sizes (ft)	15.5144	15.5144
					Supported span (ft)	17.876	17.876
					Supported area (m2)	6306	6306
					Live load (psi)	0.35	0.35
				3.3.5 C5			
					Number of bays per row	12	12
					Number of rows	12	12
					Floor to floor height (ft)	15.621	15.621
					Bay sizes (ft)	15.5144	15.5144
					Supported span (ft)	17.88	17.88
					Supported area (m2)	2588	2588
					Live load (kPa)	2.4	2.4
A23 Roof	3387.109832	m2	4.1 Roof				
				4.1.1 R1			
					Width (ft)	667	667
					Span (ft)	26	26
					Live load (psi)	0.5	0.5
					PVC Roofing Membrane (in)	-	13
					Vapour Barrier	-	1/8"
				4.1.2 R3			
					Width (ft)	135.136	608.7
					Length (ft)	135.136	30

					Concrete (psi)	3600	3600
					Concrete flyash %	AVERAGE	AVERAGE
					Thickness (ft)	0.492	0.492
					Rebar	20M	20M
					PVC Roofing Membrane (in)	-	13
			4.2 Extra Materials				
				4.2.1 Parallam			
					Parallam Columns (m3)	122.5 (including beams, crossbeams, columns)	122.5
			4.3 Concrete Column/Beams				
				4.3.5 C5			
					Number of bays per row	12	12
					Number of rows	12	12
					Floor to floor height (ft)	15.621	15.621
					Bay sizes (ft)	15.5144	15.5144
					Supported span (ft)	17.88	17.88
					Live load (psi)	0.35	0.35
			4.4 Curtain Roof				
				4.4.1 MP1			
					Wall type	Curtain	
					Length (ft)	29.25	29.25
					Height	29.25	29.25
				Openings	Total opening area	0	0
					Doors	0	0
					Windows	0	0
					Material		Fiberglass
					Type		batt
					Thickness(mm)		189
A31 Walls Below grade	2497.234	m2	5.1 Concrete Block wall				
				5.1.1 W1			
					Wall Type	Basement	Basement

					Length (m)	275	275
					Height (m)	4.25	4.25
				Openings	Total opening area (ft^2)	0	0
					Doors	39.36	39.36
					Category	-	Cladding
					Material	-	Brick
					Type	-	(metric) Modular
				5.1.2 W2			
					Wall Type	Basement	Basement
					Length (m)	115	115
					Height (m)	6.54	6.54
				Openings	Total opening area (ft^2)	0	0
					Doors	13.12	13.12
					Category	-	Cladding
					Material	-	Brick
					Type	-	(metric) Modular
				5.1.3 W3			
					Wall Type	Basement	Basement
					Length (m)	237	237
					Height (m)	2.432	2.432
				Openings	Total opening area (ft^2)	0	0
					Doors	0	0
					Category	-	Cladding
					Material	-	Brick
					Type	-	(metric) Modular
A32 Walls Above Grade	9564.19	m2	6.1 Cast-in-place				
				6.1.1 W4			
					Wall Type	Ground Floor	Ground Floor
					Length (m)	267	267
					Height (m)	5	5
				Openings	Total opening area (m2)	257	257
					Frame Type	Aluminum	Aluminum
					Glazing Type	Double Glazed	Double Glazed
					Doors	15	15

				Envelope	Category	-	Cladding
					Material	-	Brick-split faced
					Catetory	-	Insulation
					material	-	Fibreglass batt
					Category	-	Vapour barrier
					Material		Polyethylene 3 mil
				6.1.2 W6			
					Wall Type	Second - Fourth (Outside)	Second - Fourth (Outside)
					Length (m)	1823.68	1823.68
					Height (m)	4.25	4.25
				Openings	Total opening area (m2)	-	800
					Frame Type	Aluminum	Aluminum
					Glazing Type	Double Glazed	Double Glazed
					Doors	0	0
				Envelope	Category	-	Cladding
					Material	-	Brick-split faced
					Catetory	-	Insulation
					material	-	Fibreglass batt
					Category	-	Vapour barrier
					Material		Polyethylene 3 mil
			6.2 Curtain walls				
				6.2.1 W9 (Curtain Wall)			
					Length (m)	74.35	74.35
					Height (m)	4.25	4.25
					Doors	7	7
				6.2.2 W10 (Curtain Wall 2)			
					Length (m)	38.25	38.25
					Height (m)	4.25	4.25
					Doors	1	1
B11 Partitions	21434.25	m2	7.1 Steel stud walls				
				7.1.1 W8			
					Wall Type	Second - Fourth (Inside)	Second - Fourth (Inside)
					Length (m)	3553	3553

					Height (M)	4.25	4.25
				Openings	Total opening area (ft^2)	0	0
					Doors	381	381
				Door Opening Envelope	Category	-	Insulation
					Material	-	Fiberglass
					Type	-	batt
					Thickness	-	140
					Category	-	Vapour barrier
				Window opening envelope			
				7.1.2 W5			
					Wall Type	Second - Fourth (Inside)	Second - Fourth (Inside)
					Length (m)	368	368
					Height (m)	4.25	4.25
				Openings	Total opening area (ft^2)	0	0
					Doors	20	20
					Category	-	Cladding
					Material	-	Brick
					Type	-	(metric) Modular
				7.1.3 W7			
					Wall Type	Ground Floor	Ground Floor
					Length (m)	708	708
					Height (m)	5	5
				Openings	Total opening area (m^2)	-	103.5
					Doors	69	69
				Envelope	Category	-	Insulation
					Material	-	Fiberglass
					Type	-	batt
					Thickness	-	140
			7.2 Cast-in-place concrete				
				7.2.1W11			

					Wall Type	Ground Floor	Ground Floor
					Length (m)	246	246
					Height (m)	5	5
				Openings	Total opening area (m^2)	-	16.5
					Doors	11	11
				Envelope	Category	-	Insulation
					Material	-	Fiberglass
					Type	-	batt
					Thickness	-	140

Impact Estimator Input Assumptions

1 Foundation	This building element was left unchanged from the 2009 model including the following description: the foundation was broken down into footings, strip footings, and slab on grade concrete pads. The concrete footings and strip footings were named the same as the architectural drawings (i.e. F1, F2…). Any concrete footings not listed in the structural legend were named CF1, CF2, and so on, while any strip footings not listed were named SF1, SF2, and so on. The footings were calculated using the count feature in OnScreen, and the length of the footing was then multiplied by the amount of footings of each type. The impact estimator restricted the height of the footings. If a footing was larger than the allowed height, it was divided by two while the length was multiplied by two. Rebar presented a problem if the reinforcing was greater than 20M bars. The impact estimator only allowed for 10M, 15M, and 20M bars in the footings. Therefore, anything larger than 20M was considered 20M while anything smaller than 10M was considered 10M. The concrete pads were not slabs. They were similar to the concrete footings. However, they were only 100mm thick. They were named CP1, CP2, and so on. The concrete was assumed to be 20MPa as no information was given. Fly ash was assumed to be “average”, which is an option when entering concrete data in the impact estimator.

	1.1 Concrete Footing		
		1.1.1 F1	
		1.1.2 F2	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 5.
			L=(Cited Length)*(# of Footings of That Kind)
			L=(4.92ft)*5
			L=24.6ft
		1.1.3 F3	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 3.
			Similar to 1.2.2 F2
		1.1.4 F4	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 2.
			Similar to 1.2.2 F2
		1.1.5 F5	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 3.
			Similar to 1.2.2 F2

		1.1.6 F6	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 3.
			Similar to 1.2.2 F2
		1.1.7 F7	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 8.
			Similar to 1.2.2 F2
		1.1.8 F8	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 12.
			Similar to 1.2.2 F2
		1.1.9 F9	
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 7.
			Similar to 1.2.2 F2

		1.1.10 F10			
		1.1.11 F11			
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 5 and again by 2 to account for the thickness being reduced by a division of 2.		
			L=(Cited Length)*(# of Footings of That Kind)*(# Thickness Divided By)		
			L=(4.92ft)*8*2	Note: T = 1.968ft/2 = 0.984ft	
			L=78.72ft		
		1.1.12 F12			
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 8.		
			Similar to 1.2.2 F2		
		1.1.13 F13			
			The length of this footing was adjusted to account for the multiple footings of this type. The measured width and thickness were maintained, however the length was multiplied by 2.		
			Similar to 1.2.2 F2		
		1.1.14 F14			
		1.1.15 F15			
			The length of this footing was adjusted to account		

			for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.16 F16	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.17 F20	
		1.1.18 F21	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.19 F22	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall

			within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.20 F23	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.21 F24	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.22 F25	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being

			reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.23 F27	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.24 F28	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.25 F29	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 3 to account for the thickness being reduced by a division of 3.
			Similar to 1.2.11 F11

		1.1.26 F31	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.27 F32	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.1.28 F33	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.
			Similar to 1.2.11 F11
		1.2.29 CF1	
			The length of this footing was adjusted to account for the multiple footings of this type, and/or

			because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 3 to account for the thickness being reduced by a division of 3.		
			Similar to 1.2.11 F11		
		1.2.30 CF2			
			The length of this footing was adjusted to account for the multiple footings of this type, and/or because the thickness of the footing did not fall within the limits of the EIE. The measured width was maintained, however the length was multiplied by 2 to account for the thickness being reduced by a division of 2.		
			Similar to 1.2.11 F11		
	1.3 Concrete Strip Footing				
		1.3.1 F30			
		1.3.2 SF1			
		1.3.3 SF2			
		1.3.4 SF3			
	1.4 Slab on Grade Concrete Pad				
		1.4.1 CP1			
Lowest Floor	2.1.1 Slab on Grade				
	As the 150 mm thickness is not an option in the Impact Estimator, the total area of the slab on grade was multiplied by 1.5 and the dimensions entered as a 100 mm slab. As the area 'on grade' is actually the basement and part of the ground floor, the suspended area of the				

<table>
<tr><td></td><td colspan="3">ground floor was subtracted and modeled as a separate floor. The remainder was included in the A21 element. However, the IE model for the whole building combined the two floors again.</td></tr>
<tr><td rowspan="4">3Floors</td><td colspan="3">Five upper floors were modeled, the ground to fourth floors, and the bridge spanning the atrium. The bridge was modeled separately as an artifact of the 2009 model. The building envelope data was not available for the floors, and therefore average industry standards were assumed. Stairs were assumed to be steel and an area was determined from Lin's 2010 estimate and the unit weight of rolled steel was used (7850 kg/m3).
The floors were measured using area conditions. Much like in column and beams, the Impact Estimator calculated the thickness of the material based on some basic variables regarding the assembly. These include; floor width, span, concrete strength, concrete flyash content and live load. Another assumption that had to be made in this assembly group was setting the concrete strength to 20 MPa, instead of the specified 25 MPa. This was due to the IE’s limitation to model only 20 MPa, 30 MPa or 60 MPa concrete strengths. Spans were also limited to no more than 10 meters. If a span was greater than 10 meters, the total area was then divided by 10 meters to determine the resulting length. A suggested improvement is to model the floors as 20 MPa and 30 MPa and take the average assuming no better LCI is found.</td></tr>
<tr><td colspan="3">6.1 Extra Materials</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Galvanized Sheet decking</td></tr>
<tr><td></td><td>Used Lin's estimates of 1.2*0.25*0.02m by 169 m of staircase, at 7850 kg steel/m3</td></tr>
<tr><td>3 Mixed Columns & Beams</td><td colspan="3">All columns were named C followed by the number in which they were entered (i.e. the first column is C1). The method used to measure column sizing was completely depended upon the metrics built into the Impact Estimator. That is, the Impact Estimator calculates the sizing of beams and columns based on the following inputs; number of beams, number of columns, floor to floor height, bay size, supported span and live load. A grid system of columns had to be assumed even though it</td></tr>
</table>

	did not necessarily exist. An area that appeared to have a slight order to the column distribution was squared off and averaged for span between columns. For example, the foundation columns were broken into three areas. The main atrium in the FSC is an L-shape. The eight columns in the atrium were assumed to be one long line of columns with the spacing between them averaged as the span and the distance to the surrounding walls averaged as the bay size.		
	3.1 Concrete Column/Beams		
		3.1.1 C1	
			Because of the variability of bay and span sizes, the column bay and span size was estimated using multiple grid systems throughout the FSC.
		3.1.2 C2	
			Because of the variability of bay and span sizes, the column bay and span size was estimated using multiple grid systems throughout the FSC.
		3.1.3 C3	
			Because of the variability of bay and span sizes, the column bay and span size was estimated using multiple grid systems throughout the FSC.
		3.1.4 C4	
			Because of the variability of bay and span sizes, the column bay and span size was estimated using multiple grid systems throughout the FSC.
		3.1.5 C5	
			Because of the variability of bay and span sizes, the column bay and span size was estimated using multiple grid systems throughout the FSC.

4 Walls	Walls were either concrete block, wood, or concrete brick. However, each wall was labeled W followed by the number in which it was entered (i.e. the first wall was called W1). They were linear measurements, with the height measured from the profile drawings. Floors two through four were the same height, and so walls continuing through these three floors were considered one wall with a height three times the single floor height. Openings included windows and doors. Interior walls were assumed to have 400 m2 of window area. Exterior walls were measured by using one meter strips. OnScreen will measure the length of wall accounted for while using a line thickness equal to one meter. For example a 10 meter high wall 5 meters long would have a wall area of 50 meters squared. Area conditions were utilized to calculate the percent glazing area for the curtain walls, as well as the areas of the window openings. Windows were not counted directly, but instead the area of openings for windows was determined using the area function, and then divided by an average exterior window size. These assumptions were made so that a reasonable estimate could be made within the timeframe given. Some other assumptions and calculations were made in order to complete modeling of the walls for the FSC building, such as affecting the length of the concrete cast-in-place walls to accommodate the wall thickness limitation in the IE, and the assumption that interior steel stud walls were heavy gauge (25Ga).		
	2.1 Concrete Block Wall		
		2.1.1 W1	
		2.1.2 W2	
		2.1.3 W3	
		2.1.4 W4	
	2.2 Steel Stud Walls		
		2.2.1 W5	
			Since this was an interior wall, 89mm thick Fiberglass Batt was assumed. It is also assumed

			that it is steel studs throughout the interior walls. No gypsum board was assumed to be present.		
	2.3 Conrete Brick Walls				
		2.3.1 W6			
	2.4 Steel Stud Walls				
		2.4.1 W7			
			Since this was an interior wall, 89mm thick Fiberglass Batt was assumed. It is also assumed that it is steel studs throughout the interior walls.		
		2.4.2 W8 (w/ Veneered Face)			
			Since this was an interior wall, 89mm thick Fiberglass Batt was assumed. It is also assumed that it is steel studs throughout the interior walls.		
		2.4.3 W9 (Curtain Wall)			
			The total length of the curtain walls were measured linearly from the floor plans. The average height of the FSC was then multiplied by the length to determine an average area. It was assumed that only one door for the east entrance is present.		
		W10 (Curtain Wall)	Measured using Onscreen and entered as total length over the floors by 4.25 m		
5 Roof	The roof was modeled using area conditions. The roof of the FSC was divided into three inputs, a suspended slab for the main roof, an open web steel joist system, and glazing for the large skylight. Once again the concrete strength was set to 20 MPa instead of the specified 25 MPa. The skylight was modeled as a curtain wall as there is no skylight option in the IE. The steel roof assumed the standard commercial option.				
	5.1 Roof				
		5.1.1 R1			

			Because of the limitations of the Impact Estimator, spans were reduced to 30 ft. This was done by maintaining the same roof area, but reducing the span to 30 ft and increasing the length to account for the reduction.
			Similar to 4.1.1 FL1
		5.1.2 R2	
			Because of the limitations of the Impact Estimator, spans were reduced to 30 ft. This was done by maintaining the same roof area, but reducing the span to 30 ft and increasing the length to account for the reduction.
			Similar to 4.1.1 FL1
6 Extra Materials	The large Parallam columns within the FSC are not supporting any significant load save the additional beams. Their main purpose is aesthetics only. When entering the Parallam column grid into the EIE, the loads that the columns are calculated to take would be greatly exaggerated. Since the Parallam columns are not used for structural support, they were added to extra base material. The length calculator in OnScreen was used and the columns were then multiplied by their average thickness. To account for uncertainty, an additional 5% was added.		
	6.1 Extra Materials		

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