Fred Kaiser Building

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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.

If further information is required, please contact the course instructor Rob Sianchuk at rob.sianchuk@gmail.com

CIVL 498C – FINAL PROJECT

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[redacted]

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Executive Summary

This summary precedes the report which constitutes a part of the UBC LCA project. This is a student-completed project by Nick Gagliano as a technical elective in the Faculty of Applied Science at the University of British Columbia.

As part of coursework in CIVL 498C, this final project constitutes the main deliverable: a critical review of a prior student's work and a plethora of research on Life Cycle Assessment (LCA). In prior years, students had completed LCA models of various academic buildings on campus to varying degrees of accuracy and presented them in a report. This year, each student was assigned a building and the task is to critically review and update the model, and work towards formulating a benchmark for future planning decisions. The building I reviewed was the Fred Kaiser Building (Kaiser).

Methods of corroborating the values presented in the original model included revisiting the annotated construction drawings in OnScreen TakeOff where the original modeller did their takeoffs, comparing these to the Inputs and Assumptions document and the actual Athena model, and iterating back-and-forth between all these forms of data. My model was fraught with errors due to carelessness (wrong numbers with no assumptions entered) and takeoffs that didn`t even exist as well as missing construction drawings. In order to complete this project, many assumptions were made and I did the best to complete this in the time constraints provided.

The results of the LCA model were then used to both establish a benchmark and then make comparisons between our individual models and the benchmark. In the report, many conclusions about the data are presented. The main ones are that

1. There was some confounding factor skewing the A11 Foundation values by over 90% from the benchmark.
2. In terms of newer construction, Kaiser is one of the lower-cost, lower impact options which serves as a good design example for future buildings
3. In general, results for the Kaiser building were very different from the benchmark (no conclusions can be drawn from this)

The final sections of this report highlight methods to operationalize LCA at UBC and make use of the benchmarking we did in this class in real life.

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1.0 General Information on the Assessment

Purpose of the assessment

This Life Cycle Assessment (LCA) of the Fred Kaiser Building at the University of British Columbia (UBC) was conducted originally by Donqui Liao in 2010 and later critically reviewed by myself.

The intended use of this single LCA study is to quantify the environmental impact of the Fred Kaiser building from “cradle-to-gate” for the basic structure and envelope (not including mechanical & electrical systems, tenant fit-outs, energy use, or decommissioning and disposal). As well, the depth of the LCA analysis divided into Canadian Institute of Quantity Surveyors (CIQS) Level 3 elements and materials allows a high degree of granularity in examining which elements have the greatest impact.

This study was completed to not only quantify the impact potential of one building and its elements, but ultimately to be one source for an aggregate benchmark of buildings at UBC. This will help to quantify environmental impacts and provide design rationale in sustainability to UBC decision-makers.

The intended audience of this study and the benchmark study is the UBC Planning and Sustainability Office decision-makers as this study informs their prior and future decisions in a quantitative manner related to sustainability. Other audience members will obviously be Rob Sianchuk (CIVL 498C course instructor and grader of this assignment) and architects, engineers, and fellow professionals with an interest in sustainability.

Inherent in this study’s purpose is its use for comparative assertions. Given that the LCA of Fred Kaiser building will be used to establish a benchmark, it will be immediately used to compare and generate more aggregate statistics. As well, it will be used as a model to compare future designs to: all which indicate its use for comparison.

The data requirements of this study are not required to be extremely precise as this will be used as a high-level planning and decision-making tool to minimize environmental impact potential: not to quantify exact values of each kilogram of material. Given its use for conceptual planning and programming, there is no need for our studies to have extremely refined datasets. Since all the studies that will be benchmarked together used the same Athena Life Cycle Inventory (LCI) database and the same mid-point life cycle impact assessment (LCIA) methodology (US EPA TRACI, 2007) they are all comparing similar information at the same granularity.[1] Furthermore, given that we are reporting values only for CIQS Level 3 elements of the structure and envelope and then aggregating them across many buildings: any erroneous assumptions one makes for a single building or element will be negligible in the overall statistics.

Identification of building

This building analyzed is the Fred Kaiser Building at the University of British Columbia (UBC). It was completed and opened on September 15, 2005 and is located at 2332 Main Mall. It is a 5-storey, 9026 m^2 concrete and glazed curtain wall structure with a primary purpose of centralizing engineering

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[1] Athena Sustainable Materials Institute. (2013). Retrieved from http://www.athenasmi.org/our-software-data/overview/

administrative offices (such as Engineering Student Services and the Dean of Applied Science's Office) and providing space for the then-rapidly growing faculty of electrical and computer engineering. The building's total funding cost was $26 million, with a generous $4 million donation from Mr. Fred Kaiser – who the building is thus named after.[2]

This $26 million cost dates to 2005, when the building was constructed. Using the net present value calculation listed below, the net present value of the Fred Kaiser building in 2013 is $30.9 million. I am unsure if this is the correct method of calculation but the information to calculate this was provided to us the weekend that the project was due.[3]

$$NPV = Building\ cost\ in\ 2005 * \left(\prod escalation\ rate\ from\ 2006 - 2013\right)$$

$$NPV = 26M * (1.13 * 1.09 * .93 * .95 * 1.04 * 1.04 * 1.01)$$

$$NPV = \$30.9\ million$$

The time to construct this building was just over 2 years: from start of demolition to dedication with a project team of Omicron Consulting Group (Architects), Bush Bohlman & Partners (Architects), and Scott Construction (Construction Manager).[4]

Other Assessment Information

The table below provides a summary of information relative to this assessment.

Table 1: Assessment Information

Client for Assessment	Completed as part of CIVL 498C – a technical elective at UBC
Name and qualification of the assessor	Nick Gagliano – Student in BASc. (Civil Engineering) Donqui Liao (Previous Author)
Impact Assessment method	US EPA TRACI Version 2.2 (2007)[1]
Point of Assessment	Over 8 years since building dedication
Period of Validity	5 years.
Date of Assessment	Completed in December 2013.
Verifier	Student work, study not verified.

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[2] UBC Faculty of Applied Science. (2005, Sep 15). *UBC's Fred Kaiser Building opens, Engineering expands. Retrieved from http://apsc.ubc.ca/apsc/news/2005/09/ubc%E2%80%99s-fred-kaiser-building-opens-engineering-expands*

[3] Sianchuk, R. (2013). *Net Present Value Calculation Procedure* [PDF Document]. Retrieved from http://civl498c.wikispaces.com/file/view/NPV%20Calculation%20Procedure.pdf/469705562/NPV%20Calculation%20Procedure.pdf

[4] Brunet, Robin. (2005, Apr). *Fred Kaiser Building – UBC*. Retrieved from omicronaec.com/wp-content/uploads/2013/01/Fred_Kaiser_Building_UBC_Awards_Magazine.pdf

2.0 General Information on the Object of Assessment

Functional Equivalent

A functional unit is a performance measure of the analyzed product system to be used as a reference unit and normalization factor. The following example is most illustrative of what the aforementioned means.

Given some amount of manufactured floor tile of brand A, there is some set amount of environmental impact potential throughout its life cycle (from resource extraction to disposal). From this example, it is obvious the net amount of impact is proportional to the amount of tile: the more tile, the greater the impact (assuming all else is constant). Therefore to compare the impact potential of 200 m^2 of tile A with 500 m^2 of tile B is not a fair means of comparison using total values. Given that the primary function of tiles is to cover some gross floor area of Y m^2, one can normalize the total impact per tile brand by the gross area to determine the impact potential per unit area. This is now a fair means of comparison as the functional unit (square metres of floor area) normalizes the data.

In our study, we defined different building elements as having different functional units (such as m^2 of wall area for partitions and m^2 of floor area for upper floor construction). Each building element has a different use, and its functional unit should match this closely. This is important, as in the example above, to normalize the impact potential of different buildings and elements to provide a fair means of comparison.

Table 2: Functional Equivalent Definition Template

Aspect of Object of Assessment	Description
Building Type	An academic building at UBC
Technical and functional requirements	An institutional, academic building at UBC. Must meet National, Provincial and Local building and energy code. Building incorporated green technologies such in-slab radiant heating. Primarily office and research space with large atria and services for both students (lab space) as well as administrative offices. Starbucks located inside[5]
Pattern of use	Occupancy of 700 people for research and lab space for Electrical and Computer Engineering and office space for the Dean of Applied Science and other administrators.[5]
Required service life	The building service life was not specified on drawings: assume 100 years for structure and envelope[6]

Reference Study Period

According to EN 15978, the reference study period should the required service life of the building and all deviations need to be expressly stated. The required service life of all buildings at UBC is 100 years for

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[5] Omicron Consulting Group. (2013). *The Fred Kaiser Building at UBC.* Retrieved from http://omicronaec.com/omicron-projects/the-fred-kaiser-building-at-ubc

the structure and envelope as specified in the UBC Technical guidelines. This was the best technical source I could find on service life, while many others in class discussed a 60 year service life.[6]

In our study, the service life is set to 1 year so that replacement cycles, maintenance, and use are not considered: only the "cradle-to-gate" (material extraction to structure and envelope construction) impacts are considered. Our study excludes EN 15978 Modules B, C, and D (Use, end-of-life, and benefits) phase as there is a lack of data on the energy usage of individual buildings and uncertainty in the end-of-life demolition and recycling of building materials.

Given that the Kaiser building energy usage was not provided, it is impossible to determine accurately the Use phase impact. If this information were provided, it could simply be input into the Impact Estimator in terms of KWh and Joules for different energy sources to create a model of the impacts: this information would need to be obtained from UBC Plant Operations. Also, during building use, Athena has pre-determined building component replacement cycles and maintenance which may differ vastly from the realities on a UBC project. Given this large uncertainty, this is another reason for discounting Module B (Use phase).

Modules C and D (End-of-life and benefits) are not a part of the LCA because it is only a "cradle-to-gate" analysis. Given that the Kaiser building was built in 2005, it mostly likely will not be fully decommissioned until at least the year 2100. There is such a large uncertainty on this time-scale, in terms of future technologies for reuse and demolition, that the results for end-of-life would be meaningless.

Object of Assessment Scope

The Fred Kaiser Building is a five-storey concrete frame building with large amounts of glazed curtain wall as the exterior envelope. The primary purpose of this building is as an academic space: used for offices, classrooms, and research facilities.

The foundations were all composed of reinforced concrete as the basic building material: the majority of these were spread footings and a few strip footings. The lowest floor construction consists of a concrete slab-on-grade and the upper floor construction is the concrete columns and beams, as well as suspended slabs which it supports. The wall below grade was a cast-in-place perimeter wall to retain the soil. The walls above grade were mostly glazed curtain wall, and some concrete tilt-up panels. The roof consisted of a suspended concrete slab supported by steel HSS columns. On each floor, there were partition walls (defined as all load-bearing and non-bearing walls on the interior): ranging from steel stud and drywall to cast-in-place concrete to concrete block. In terms of external works, the Fred Kaiser building is attached to and bordered by other existing structures, so aside from utilities and small patching of landscape near the entrance, there was very little external work.

The purpose of this study is only to examine the structure and envelope because uncertainty in modelling for these components can be minimized by only analyzing these (structure and envelope fall

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[6] University of British Columbia. (2013). *UBC Technical Guidelines Performance Objectives.* Retrieved from http://www.technicalguidelines.ubc.ca/technical/performance_obj.html

into a fairly standard scope which the Impact Estimator (IE) does model). This runs contrary to the recommendations of EN15978, but given that this is an undergraduate course for those learning LCA: I believe it is fair to exclude external works from the scope due to complications and lack of time. IE does not model other finishings, HVAC systems, etc. and these would all have a high variability from product-to-product in terms of their impact potential. For simplicity and accuracy of analyzed items, this study is limited to structure and envelope. Problems would arise in external works, especially in a densely-populated area such as UBC, as to the allocation of impact potential for adjacent buildings sharing this space. If external works needed to be analyzed for some reason, a future LCA practitioner could select whichever external features throughout UBC they wanted to examine and reach their own conclusions easily. The use of the modified version of CIQS Level 3 allows decision-makers to see where the primary areas contributing to impact potential are in the building, and provides a logical way of segregating building components based on their function (see Table 5 for reference unit of each of these quantities).

Table 3: Building Definition Template

CIVL 498C Level 3 Elements		**Description**	**Quantity (Amount)**	**Units**
A11	Foundations	Strip and pad footings	2,704	m^2
A21	Lowest Floor Construction	Slab-on-grade (SOG)	2,704	m^2
A22	Upper Floor Construction	Concrete Columns, beams, suspended slabs, HSS columns	10,464	m^2
A23	Roof Construction	Roof slab (see assumptions why columns not included due to poor .OST and assumptions of previous modeller)	2,699	m^2
A31	Walls Below Grade	Exterior walls below grade: cast-in-place	529	m^2
A32	Walls Above Grade	Exterior walls above grade: primarily glazed curtain wall with some concrete tilt-up	3,609	m^2
B11	Partitions	All interior walls: cast-in-place, concrete block, and steel stud	14,875	m^2

3.0 Statement of Boundaries and Scenarios Used in the Assessment

System Boundary

The system boundary determines the processes which are accounted for and analyzed in the assessment. Only Modules A 1-3 (Product Stage) and A 4-5 (Construction Process stage) are included in our models (names defined in EN 15978).[7] Modules B, C, and D correspond to Use, End-of-Life, and

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[7] Sianchuk, R. (2013). *Life Cycle Assessment Project Outline* [PDF Document]. Retrieved from http://civl498c.wikispaces.com/file/view/Stage%204%20Outline_291013.pdf/464589706/Stage%204%20Outline_291013.pdf

Supplementary information and were not included in our study. Since the service life of the building was input into Impact Estimator as 1 year and no energy usage was input, only Module A was accounted for in our LCA.

Module A1 (Raw Material Supply) is supported by the upstream processes of initial land surveying and exploration (eg. test wells), construction of the original facility for extraction of raw resources, and the movement of people and ecosystems to accommodate the new facility for raw resource extraction. The downstream processes are preparation and conversion of products and packing for transport.

Module A2 (Transport) is supported by the upstream processes of preparation and conversion of raw products into useable sources for packing. The downstream processes are the receiving of packaged, shipped materials at the manufacturer.

Module A3 (Manufacturing) is supported by the upstream processes of preparing materials for manufacturing (eg. unwrapping of packaging and sorting). The downstream processes are disposal of wastes from manufacturing and preparing shipment to the construction site.

Module A4 (Transport) is supported by the upstream processes of material preparation as in A2. The downstream processes are the receiving and accounting for the products on the construction site.

Module A5 (Construction-installation process) is supported by the upstream processes of receiving the materials and coordination of trades and labour to complete this work. The downstream processes are the use of these building elements throughout the useful, service life of the building.

Product Stage

The product stage describes the process from resource extraction to complete manufacturing of the product before it is shipped on-site. It considers the following facets:

First, it includes raw resource extraction and the quantification of air, water, and land emissions per unit of extracted resource (including long-term benefits of restoration of the same area after extraction life is complete). The transportation of the product from the extraction point to the manufacturer is included and typically accounts for the largest proportion of impacts throughout the cycle of a building product. It accounts for all processes from the initial shipment to manufacturer through final processing. Finally, all the processes that occur at the manufacturer`s plant is accounted for in this stage as well. The boundary between this stage and the construction stage is that the construction stage includes the transportation of the product from the manufacturer to the construction site itself.[8]

Production of ancillary materials and pre-products can or cannot be included in LCI data based on system boundaries established by the modeller. From a corrugated packing LCA that was reviewed,

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[8] Athena Sustainable Materials Institute. (2013). *Technical Details.* Retrieved from http://www.athenasmi.org/resources/about-lca/technical-details/

containerboard mills and converting plant ancillary materials from the product stage were included. We can thus glean that our LCI database follows a similar trend to include ancillary materials.[9]
From one of the articles on the Athena Institute`s website, information can be gleaned on whether generation of energy input is considered in the study or not. The reviewed article is about steel-making and discusses how different types of blast furnaces require different amounts of energy and wildly affect the LCA data for steel. From this report then, we can assume that the LCI data includes the generation of energy input.[10]

Waste is another element considered in the LCI data (both on-site and off-site disposal). From a life cycle study on particleboard, they included both on-site and off the plant as well as within the plant waste movement in their system boundary. This study was created by Athena and therefore it is a good assumption that their LCI data would also include this.[11]

Finally, packaging is also another item considered in LCI data. In a LCA on Canadian particleboard (referenced above), packaging is one of the modules they considered. Again, since this is a study written by Athena, it is very likely that our LCI data also includes this.[11]

Construction Stage

The construction stage describes the process from the factory gate for each construction product to final assembly in the structure. The transport and construction installation modules considers the following facets:

The example of cast-in-place concrete on a construction site in the Athena Software and Database Over view (p.19) provides a great working example as to what is included in the construction stage. The following insights all reference this example in expressing which facets are and are not included in the construction stage.[12]

Transportation from the manufacturer to the construction site for each product is calculated and factored into the given LCI data. It uses regional averages for different products, hence, specifying the correct location in the Impact Estimator is important in determining the distances for products to the

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[9] PE-Americas and Five Winds International. (2010 February).*Corrugated-packaging Life Cycle Assessment Summary Report.* Retrieved from http://www.corrugated.org/upload/LCA%20Summary%20Report%20FINAL%203-24-10.pdf

[10] Markus Engineering. (2002). *Cradle-to-Gate Life Cycle Inventory: Canadian and U.S. Steel Production by Mill Type.* Retrieved from http://www.athenasmi.org/wp-content/uploads/2011/10/1_Steel_Production.pdf

[11] Athena Sustainable Materials Institute. (2013). *A Cradle-to-Gate Life Cycle Assessment of Canadian Particleboard-2013 Update.* Retrieved from http://www.athenasmi.org/wp-content/uploads/2013/10/CtoG-LCA-of-Canadian-PB-Update.pdf

[12] Athena Sustainable Materials Institute. (2013 April). *Athena Impact Estimator for Buildings V4.2 Software and Database Overview.* Retrieved from http://calculatelca.com/wp-content/uploads/2011/11/ImpactEstimatorSoftwareAndDatabaseOverview.pdf

construction site. As indicated in the above example, a round trip for concrete and rebar delivery was assumed. [13]

Storage of products and provisions such as heating, cooling, humidity, etc. are another facet considered in this stage. For wood installation, this may be keeping products dry and stored close to their equilibrium moisture content to prevent swelling, or for drywall ensuring it doesn't get cold and wet. As indicated in the above example, temporary heating is considered for concrete that is poured in cold weather.

Installation of products and on-site transformation of construction products (including ancillary materials) is also part of this stage. This can include temporary wood support structures, formwork, and ties and fasteners which will not constitute a part of the final product. As indicated in the above example, formwork and its degradation over time is considered in the LCI data.

Waste management is a final section considered in this stage. This includes left-over scraps of wood, drywall, and other materials cut on-site for disposal as well as leftover concrete and other materials that need to be shipped back to suppliers. This is all accounted for in the LCI data. As indicated in the above example, spilled concrete and concrete that needs to be sent back to the supplier is all account for.

4.0 Environmental Data

Data Sources

The LCA study we conducted used the Impact Estimator which used the Athena LCI Database for material process data and the US LCI database for energy and pre-combustion processes and transportation.[7]

The Athena LCI Database is similar to the US LCI Database and even includes data from it. The Athena Institute has invested over $2 million to research, develop, and continually improve their database. Independent research is coordinated with industry to conduct regionally-sensitive life cycle inventories. This database is managed by the Athena Institute.[14]

The US LCI Database was developed in 2001 when the U.S. Department of Energy set as a priority for the National Renewable Energy Laboratory (NREL) and the Athena Institute to develop a public database: which has since been publicly available since 2003. The goal of this is to provide a national public database with a consistent methodology to compare similar data collection and analysis methods via

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[13] Athena Sustainable Materials Institute. (2013). *Frequently Asked Questions.* Retrieved from http://calculatelca.com/faqs/#ie4b_project_data

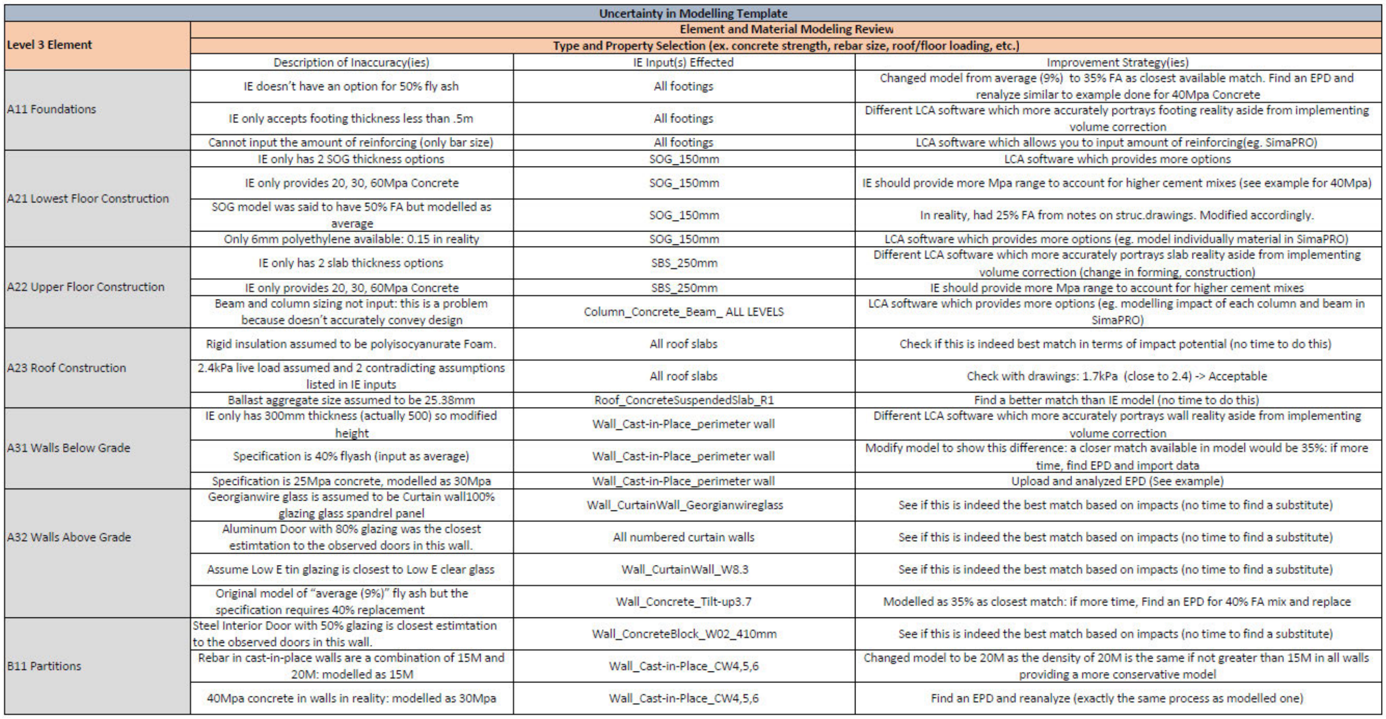
[14] Athena Sustainable Materials Institute. (2013). *Athena research teams follow common building materials from cradle-to-grave to calculate the environmental effects at each stage in the product's life cycle.* Retrieved from http://www.athenasmi.org/our-software-data/lca-databases/

critical review. Main items in its constant development include a critical review process of data, ensuring compatibility with international standards, searching for funding and constant response to user feedback. There is constant improvements via critical review and an increase in data additions. This database is managed by NREL.[15]

Data Adjustments and Substitutions

In this section, the material type and property inaccuracies are the only items discussed. Adjustments and substitutions for geometry measurements and improvements are highlighted under "6.0 Model Development". The geometry measurements and analysis of my model took an extremely long amount of time, so there was less time to focus on this section. The following table summarizes material and property inaccuracies found in my original model.

Table 4: Material Type and Property Inaccuracies found in Kaiser Building Model



Uncertainty in Modelling Template			
Level 3 Element	Element and Material Modeling Review		
	Type and Property Selection (ex. concrete strength, rebar size, roof/floor loading, etc.)		
	Description of Inaccuracy(ies)	IE Input(s) Effected	Improvement Strategy(ies)
A11 Foundations	IE doesn't have an option for 50% fly ash	All footings	Changed model from average (9%) to 35% FA as closest available match. Find an EPD and renalyze similar to example done for 40Mpa Concrete
	IE only accepts footing thickness less than .5m	All footings	Different LCA software which more accurately portrays footing reality aside from implementing volume correction
	Cannot input the amount of reinforcing (only bar size)	All footings	LCA software which allows you to input amount of reinforcing(eg. SimaPRO)
A21 Lowest Floor Construction	IE only has 2 SOG thickness options	SOG_150mm	LCA software which provides more options
	IE only provides 20, 30, 60Mpa Concrete	SOG_150mm	IE should provide more Mpa range to account for higher cement mixes (see example for 40Mpa)
	SOG model was said to have 50% FA but modelled as average	SOG_150mm	In reality, had 25% FA from notes on struc.drawings. Modified accordingly.
	Only 6mm polyethylene available: 0.15 in reality	SOG_150mm	LCA software which provides more options (eg. model individually material in SimaPRO)
A22 Upper Floor Construction	IE only has 2 slab thickness options	SBS_250mm	Different LCA software which more accurately portrays slab reality aside from implementing volume correction (change in forming, construction)
	IE only provides 20, 30, 60Mpa Concrete	SBS_250mm	IE should provide more Mpa range to account for higher cement mixes
	Beam and column sizing not input: this is a problem because doesn't accurately convey design	Column_Concrete_Beam_ ALL LEVELS	LCA software which provides more options (eg. modelling impact of each column and beam in SimaPRO)
A23 Roof Construction	Rigid insulation assumed to be polyisocyanurate Foam.	All roof slabs	Check if this is indeed best match in terms of impact potential (no time to do this)
	2.4kPa live load assumed and 2 contradicting assumptions listed in IE inputs	All roof slabs	Check with drawings: 1.7kPa (close to 2.4) -> Acceptable
	Ballast aggregate size assumed to be 25.38mm	Roof_ConcreteSuspendedSlab_R1	Find a better match than IE model (no time to do this)
A31 Walls Below Grade	IE only has 300mm thickness (actually 500) so modified height	Wall_Cast-in-Place_perimeter wall	Different LCA software which more accurately portrays wall reality aside from implementing volume correction
	Specification is 40% flyash (input as average)	Wall_Cast-in-Place_perimeter wall	Modify model to show this difference: a closer match available in model would be 35%: if more time, find EPD and import data
	Specification is 25Mpa concrete, modelled as 30Mpa	Wall_Cast-in-Place_perimeter wall	Upload and analyzed EPD (See example)
A32 Walls Above Grade	Georgianwire glass is assumed to be Curtain wall100% glazing glass spandrel panel	Wall_CurtainWall_Georgianwireglass	See if this is indeed the best match based on impacts (no time to find a substitute)
	Aluminum Door with 80% glazing was the closest estimtation to the observed doors in this wall.	All numbered curtain walls	See if this is indeed the best match based on impacts (no time to find a substitute)
	Assume Low E tin glazing is closest to Low E clear glass	Wall_CurtainWall_W8.3	See if this is indeed the best match based on impacts (no time to find a substitute)
	Original model of "average (9%)" fly ash but the specification requires 40% replacement	Wall_Concrete_Tilt-up3.7	Modelled as 35% as closest match: if more time, Find an EPD for 40% FA mix and replace
B11 Partitions	Steel Interior Door with 50% glazing is closest estimtation to the observed doors in this wall.	Wall_ConcreteBlock_W02_410mm	See if this is indeed the best match based on impacts (no time to find a substitute)
	Rebar in cast-in-place walls are a combination of 15M and 20M: modelled as 15M	Wall_Cast-in-Place_CW4,5,6	Changed model to be 20M as the density of 20M is the same if not greater than 15M in all walls providing a more conservative model
	40Mpa concrete in walls in reality: modelled as 30Mpa	Wall_Cast-in-Place_CW4,5,6	Find an EPD and reanalyze (exactly the same process as modelled one)

Most of the inaccuracies found in the model consisted of limitations in the Athena Estimator options in terms of concrete compressive strength, thickness for elements, fly ash content, and finding best fits of elements.

I made many improvements on materials and properties without updating Athena datasets: based entirely on deficiencies in the original modeller's process. Firstly, there was a systemic problem amongst modelled elements to model high fly ash volumes (above 30%) as "average (9%)" volume in Athena Impact Estimator. For such high volumes, this is not the closest match in IE's limited choices: 35% is a

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[15] Deru, M. (2009 August). *U.S. Life Cycle Inventory Database Roadmap.* Retrieved from http://www.nrel.gov/lci/pdfs/45153.pdf

closer option and I modified all elements with this deficiency. This included all footings (52 of them), cast-in-place perimeter wall below grade, and concrete tilt-up wall above grade. Secondly, many assumptions were made by the modeller on the type of glazing, insulation, and curtain wall that wasn't in IE which may not accurately reflect the nature of the products. If there were more time to complete this, I would research EPDs and publicly-available LCIA datasets and create profiles for these products (as will be shown for 25 MPa concrete in the next paragraph). Another material-type inaccuracy for A22 is the use of a pop-up window to enter the beam & column count and the span & bay width to obtain a floor-by-floor impact. This is not representative of the conditions on site as the program doesn't know the member sizes, volumes of concrete and rebar, etc. A better solution (if I had more competency in LCA methods) would be to model the volumes of material and their associated processes in a program like SimaPro to gain a full idea of the impact potential.

The one dataset that I did have time to import was a change of concrete strength from 30MPa to 25 MPa for the Perimeter Wall Below Grade. I picked this element as its large length leads to a significant volume. If any significant difference would be noticed between this small strength change, it would be in this large element. The process to complete this is as follows:

1. First, I found an Environmental Product Declaration (EPD) for 25MPa concrete on the internet. I chose 3500psi concrete (Mix 356EC9D2) from Central Concrete as it is the closest strength match to our mix.[16]
2. I input an "extra basic materials" model into IE for 30MPa concrete (the original assumed model) of 1 m^3 and found the Bill of Materials (BoM) for the amount of Concrete. From this, there is a 5% waste factor that Athena considers as extra concrete compared to the take-off of the structural element volume.
3. I input the original model of the Perimeter Wall in Athena IE (the same model as in IE Inputs) and found the volume of concrete from the BoM: this was $166.6m^3$.
4. I then scaled the volume from the actual wall by the waste factor (1.05) and input $158.7m^3$ into the "extra basic materials" volume which accounts for the overall concrete waste.
5. From this point, I exported both the original model and the "extra basic materials" summary reports in Athena and subtracted the "manufacturing" module impacts of the "extra" concrete from the wall. This yields the equivalent of an LCIA for a "hollowed out" wall (simply missing the concrete). I assumed the transport and construction modules would have the same impact as the original wall (regardless of strength) and thus did not subtract as there would be no difference for these two concretes.
6. I then manually input the data from the EPD into a new cell for each impact category and scaled it from the $1m^3$ in the study to $166.6m^3$. I assumed "total primary energy consumption" in the EPD was the same as "fossil fuel consumption" in IE. By looking at the output for 30MPa and 25MPa concrete, it can quickly be seen this assumption was incorrect: but I left this value in for

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[16] Betita, R. (2013 April 12). *Environmental Product Declaration.* Retrieved from http://centralconcrete.com/wp-content/themes/centralconcrete/images/PDFs/Central_Concrete_EPD.pdf

completeness. Since the EPD did not have the impacts for a 25MPa concrete, I used the values for the 30MPa case of “extra” concrete

7. Finally, I input this new 25MPa concrete LCIA data for the manufacturing module back into the “hollowed out” wall. This yields the full LCIA for a 25MPa perimeter wall.

Due to time constraints of this project, I did not have the opportunity to do further examples of this process. For further cases, such as 40% fly ash not present in Athena, the same process would be undertaken. See Annex E – Data Adjustments and Substitutions for Excel output to corroborate this process.

Data Quality

In defining the data quality of our studies, it is first necessary to examine the 5 types of uncertainty typical of an LCA and provide an example of each in our LCI data sources used in this course.

Data uncertainty is the inaccuracy due to collection or interpretation of collected data. In LCI, this can be random error due to the instruments in the collection of raw input and output flow values, systematic error due to the measuring process, or bias in the allocation method. In LCIA, this can be uncertainty in persistency and lifetime of substances emitted to the atmosphere and travel potential of the substance (whether that phenomena can really occur in that location). The best demonstration of this is, even for large volumes of evolved substances into the environment that lead to eutrophication, if the setting is a desert, there will be little to no effect of this (as there is no nearby water body to render eutrophic).[16] An example of this uncertainty is that instruments used to measure emissions may be calibrated incorrectly or producers may incorrectly fill out surveys thus biasing results in the LCI database.

Model uncertainty is due to simplification of the model for purposes of analysis which can range from assuming linearity of inputs to impact potential to the determination of characterization factors for varying substances. [16] All of these assumptions which go into the modelling process directly affect the accuracy of interpretation of collected data. If modelled by a linear model of inputs to impact potential, and the system really behaves according to diminishing returns, then the model will tend to under predict values for a given input – a clear source of uncertainty. An example of this uncertainty is that characterization factors may not be correct for the location in which we are using them, a tool such as SimaPro allows the modeller to adjust these accordingly.

Temporal uncertainty is changing with time and is present in the LCI phase due to the change of yearly emissions from different production processes and the shear age of the data. [16] If a component was manufactured back in the 1950s prior to strict environmental regulation, the output flows would be very different from a building according to 2010 regulations restricting environmental contaminants much more. In the LCIA phase, interpretation of impacts over time (as effect of materials compounds over time and increasing concentration) and ability for substances to diminish in the environment over time and exposure. An example of this uncertainty is the vintage of the data collected for the Athena LCI database: where ready-mix concrete and concrete block data dates to 2005. [12]

Spatial uncertainty is due to the location that processes occur: whether that be differences in population density and thus substance exposure for human health or background levels of chemicals in the atmosphere or waters. [16] These are all factors that vary from region-to-region (for example, urban to rural in terms of smog pollution). An example of this uncertainty is present for concrete and steel product data taken from Canada and the U.S. If the Impact Estimator was then applied in another country, these values from the LCI database for impact categories such as eutrophication and smog potential may have very different values due to population density and cultural values towards certain impacts. [12]

Variability between sources occurs due to differences in outputs from product processes and human interaction with substances. [16] In the LCI phase, differences in factory processes lead to different amounts of emissions and energy usage depending on their methods. In the LCIA phase, human exposure patterns dictate human response to certain substances: low concentrations can show no affect while above a certain threshold they can cause serious consequences. An example of this is that the suppliers and producers profiled by the Athena Institute represent the average, typical processes for different construction materials such as concrete block and steel members. But in reality, a contractor may source from a more sustainable supplier who uses very different processes relative to the norm.[17]

The quality of our LCA databases is high (based on the minimal research I had time to do as part of this project). The data sourced by the Athena LCI database mostly comes from data dating to 2004 and 2005, with only aluminum frame dating to 1999.[12] Due to the relative recent nature of the data, I feel that there is a high degree of quality to the data as construction and environmental regulations for concrete and steel manufacturing processes have undergone very little change in the last 10 years. Given the cursory nature of an LCI study ($\pm 10\%$) for the environmental impacts of just the structure and envelope, there is more than enough accuracy in the data provided relative to the uncertainty in our own analysis.

5.0 List of Indicators Used for Assessment and Expression of Results

The impact assessment method is a process whereby the resources and emissions for a given product that are tabulated in the LCI process are correlated to the potential to cause environmental impacts for a cause of concern. All of the emissions as raw values are then converted, based on numerous environmental models and characterization factors, to a representative indicator value that describes the potential to cause deleterious environmental effects for an impact category. Our studies, using US EPA TRACI methodology, use a midpoint assessment methodology. A midpoint assessment means that the methodology translates emission values into themes of concern (for example, that more CO2 correlates to higher global warming potential) but does not quantify the damage that will occur. Impact categories are major areas of concern to the environment and human health. In our LCA studies, we examined the following:

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[17] Bjorklund, A. (2002). Survey of Approaches to Improve Reliability in LCA. *The International Journal of Life Cycle Assessment, 7(2),* 64-65. Retrieved from http://www.infra.kth.se/fms/pdf/lca2001.12.071.pdf

1. Global warming potential is related to the ability of our emissions to absorb infrared radiation from the atmosphere and retain this heat, thus causing global warming. The category indicator (baseline value for this impact category) is kilograms of CO2 (carbon dioxide) equivalent. The cause-effect chain consists of emissions being released into the atmosphere and absorbing infrared radiation over time. The absorption of radiation heats these molecules increasing the relative temperature of the atmosphere and ultimately leading to endpoint impacts of depletion or flooding of water, change in weather patterns, and species loss.[18]
2. Ozone depletion potential is the actual loss of stratospheric ozone. The category indicator is kilograms of CFC^{-11} (chlorofluorocarbons) which is an effective substance at degrading atmospheric ozone. The cause-effect chain consists of relevant substances being emitted into the atmosphere which interacts with ozone and causes ozone depletion. The loss of this ozone allows harmful UVB radiation to penetrate to living species on Earth leading to endpoint impacts of damages on materials, skin cancer in humans, and effects on species.[18]
3. Eutrophication is the excess evolution of nutrients to the environment, leading to rampant species growth and potential ecosystem takeover by species which would not typically thrive. The category indicator is kilograms of nitrogen as it is typically the limiting nutrient to species growth in aquatic environments: thus excess nutrients causes species which shouldn't thrive in this environment to do so. The cause-effect chain is that nitrogen in air or water emissions penetrates the soils and leaches along with rainwater or via other means into aquatic systems supplying excess nutrients. Algae and aquatic weed growth becomes rampant which leads to excess toxin release and shortage of oxygen (or ultimately hypoxia) due to the large biomass. The endpoint impacts consist of death to fish and shellfish via oxygen-deficiency and toxicity to humans and other animals which ingest shellfish contaminated with these toxins.[18]
4. Acidification potential is related to the emission of airborne acidifying chemicals into the atmosphere. The category indicator is kilograms of SO2 (sulphur dioxide) equivalent as this is a typical acidifying compound. The cause-effect chain is that acidifying airborne emissions are deposed on ground either via precipitation (through acid rain) or just as dry chemical. This can cause acidification of lakes and streams by releasing acidifying H+ ions as well as changing soil parameters and rendering them toxic by leaching of nutrients, H+, and aluminum. The ultimate endpoint impacts of this are ecosystem changes and plant and animal mortality due to severely changing conditions.[18]
5. Smog Potential is the development of smog in the atmosphere. The category indicator is kilograms of O3 (ozone) equivalent which ties into the photochemical formation of ozone in the atmosphere. The cause-effect chain is that these types of airborne emissions mixed with other chemicals and radiation react to form tropospheric ozone in the atmosphere. This then leads to decreased photosynthesis and human respiration. Possible endpoint impacts of human health issues and mortality, decreased plant life and capacity exist.
6. Human Health Criteria-Air relates to airborne particulates that we can breathe in. The category indicator is kg PM2.5 (particulate matter of 2.5 micron) equivalent. The cause-effect chain is that air emissions in the atmosphere inhaled by humans leads to PM deposition in alveoli of the lungs. This PM contains harmful substances and causes bodily reactions which can lead to severe human health issues or death.[18]

7. Fossil fuel consumption is the direct or indirect energy used to transform raw resources into products. The category indicator is MJ (mega joules) of energy consumed. The cause-effect chain is that resources being converted into products require energy to be produced. This consumed energy leads greenhouse gas and other emissions with endpoint impacts similar to global warming and acid rain.[18]

6.0 Model Development

The Level 3 elements were modelled and aggregated according CIQS Level 3 elements: a construction format in Canada which separates building elements by function. They were modelled by the following process.

This semester, a student was provided with a previous LCA study, construction drawings, Impact Estimator files along with their Inputs and Assumptions, and OnScreen TakeOff files.

The original modeller used construction drawings as a representation of the built structure as the primary reference for this study. They were used for quantity takeoffs of the building structure and envelope in conjunction with OnScreen TakeOff (a computer tool to facilitate quantities) to document and count each building element contributing environmental impacts. Then this data needed to be modelled in the Impact Estimator to derive relevant LCA data about the building and each of its components. Since the software suite does not contain every building material and configuration, assumptions had to be made to model the real quantities. For this reason, an Inputs and Assumptions document was created to document these assumptions.

As the critical reviewer, my task was to simultaneously review the Impact Estimator files, the Inputs and Assumptions document, OnScreen TakeOff and the construction drawings to corroborate the valid modelling of each item in the LCA model. I would first pick a modelled building element, check its inputs and assumptions to determine the original take-off and then compare this value to the OnScreen TakeOff file. I found numerous problems: from wrong inputs, incorrect dimensions, or missing assumptions and elements all together. This required a lot of iterations between software to attempt to rectify this.

Another task as a critical reviewer was to assemble the fully modelled data by CIQS Level 3 elements which includes Foundations, Lowest Floor Construction, Upper Floor Construction, Roof Construction, Walls Below Grade, Walls Above Grade, and Partitions. The data was aggregated into these headings so that elements of a similar function and thus functional unit would be located together and their impacts could be normalized. See the following table for sorting methodology and functional unit.

Table 5: CIQS Level 3 Sorting Criteria and associated functional unit

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[18] ILCD Handbook. (2010). *Framework and Requirements and LCIA Models and Indicators.* Retrieved from http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-LCIA-Framework-requirements-online-12March2010.pdf

CIQS level 3 Elements	Criteria for categorization (not exhaustive list)	Functional Unit
A11 Foundations	A foundation for the building that is below grade (not including excavation, backfill or shoring)	square metres of slab-on-grade (SOG) area
A21 Lowest Floor Construction	Slab-on-grade, vapour barrier and slab thickening	square metres of slab-on-grade (SOG) area
A22 Upper Floor Construction	*Columns and beams (except those that support roof) , suspended slabs, and stairs *Doesn't include finishes and rails	square metres of suspended slab area on all upper floors (excluding SOG)
A23 Roof Construction	*Suspended roof slabs, columns that support roof *Doesn't include canopies and parapets	square metres of roof suspended slab area
A31 Walls Below Grade	Any exterior wall below grade	square metres of exterior wall area below grade
A32 Walls Above Grade	*Any exterior wall above grade (structural or curtainwall) *Not including finishes	square metres of exterior wall area above grade
B11 Partitions	*All interior walls *Not including cubicles and non load-bearing partitions	square metres of interior partition wall area

In Stage 3 of this project`s critical review, there were multiple tasks to be completed. The first task was the establishment of a methodology and figure to compare individual LCA studies by each Level 3 element and each impact category to the benchmark values. The next task was to identify the largest contributors in a list to global warming potential from each Level 3 element. Then, a table of model improvements and inaccuracies was created as a way to address future changes that could improve the accuracy of our LCA study.

Stage 4 is the final model development and presentation (represented in this paper). I've conducted an extensive overhaul of my model: the original which was fraught with errors. The original modeller of this project had many mistakes which can be contributed to shear carelessness. The following is a synopsis of the corrected errors (all values in purple in the IE Inputs component of the Inputs and Assumptions are values that I have modified from the original modeller). This model was fraught with so many errors, there is no possible way that I could have looked at and repaired all of them in this timeframe.

A11 Inaccuracies

The original modeller had a completely inaccurate model of the foundations for the Kaiser building: he simply modelled every footing on the footing schedule once. In reality, the building did not contain every footing type on this schedule and contained multiples of individual types (see Table 6). For strip footings, the original modeller input them into Impact Estimator (IE) as pad footings even though they clearly weren't (see Table 7 for corrections). Another mistake by the original modeller was inputting all the footing fly ash contents as "average", while the general notes on the structural drawings clearly state that the fly ash is a minimum of 50%. Given that IE does not have this option, I selected the highest option (35% fly ash) which much more accurately models this fly ash content than "average (9%)". I conducted the take-offs, modified the Inputs document, and remodelled the incorrect dimensions and missing quantities in Impact Estimator.

The footing model was so fraught with errors, I did not have time to analyze more components of it. One key missing item in my analysis was structural drawing S1.1 (or a continuation of the foundation plan past gridline L). This was not provided for the original modeller nor I; therefore, I assume it was just existing foundations of a previous structure and not important to our model.

Table 6: Missing Footing Quantities

Footing Type	Quantity Missed by Original Modeller
F1	6
F2	11
F3	5
F4	Eliminated from model: was not present on drawings
F5	6
F6	3
F8	3
F9	5
F10	2
F11	2
F12	Eliminated from model: was not present on drawings
F13	3

Table 7: Incorrect Footing Dimensions

Footing Type	Entered Dimension(m)	Corrected Dimension(m)
F11	3.3	3
F16	0.45	99
F17	0.6	13
F18	0.9	40
Footing_SF	0.45	1.4
	0.45	1.8
	250	500

<u>A21 Inaccuracies</u>
Lowest floor construction of my model consisted only of slab-on-grade (SOG) so there weren’t as many inaccuracies to check. Firstly, the SOG thickness was input incorrectly as “150mm” instead of the actual “140mm” as per the structural drawings. In the volume correction formula, this new thickness was used. This is another example of careless inputs by the original modeller, which over such a large area (about 2000 m^2), amounts to about 20 $m^3$of concrete which were over-counted.

Also, similar to the foundations, the original modeller said the SOG was 50% fly ash content modelled at “average” while the minimum value from the structural drawings is 25%. This was modified in the inputs and model accordingly to 25%.

One key missing item in my analysis was structural drawing S1.1 (or a continuation of the foundation plan past gridline L). This was not provided for the original modeller nor I; therefore, I assume it was just existing SOG of a previous structure and not important to our model.

<u>A22 Inaccuracies</u>

The upper floor construction of my model has the most uncertainties which I cannot corroborate. One key missing item in my analysis was all the structural drawings for the upper floors was not provided for the original modeller nor I; therefore, it is impossible to corroborate slab thicknesses modelled in IE nor which floors correspond to which slab thicknesses. I assumed that the titles and floor levels mentioned in the original OST file correctly matched floor area to slab thickness. All of the square footage matched up for these floors using this methodology.

In terms of determining the number of beams and columns on each floor, due to time constraints, I was unable to corroborate these values and assumed the modeller's values to be correct. Reasons this couldn't be done is due to the poor labelling of columns throughout the building in the OST file and no structural drawings of beams being provided.

Given that model element "SBS_250mm" is defined as the suspended slab on the ground and second floor, the structural drawing notes state that the live load is 3.6kPa (not 4.8kPa as the original modeller assumed). This was modified accordingly.

A23 Inaccuracies

Since the OST file does not clearly note all HSS columns, I assumed that all of the HSS columns belonged to the A22 category. This was due to 2 reasons: the time constraint of this project and that the majority of HSS was on the perimeter of upper floors not the roof. These are the reasons why I chose to put HSS columns into A22. If there were more time, I would have completed the take-off for all of the columns and distributed them between A22 and A23 accordingly.

Sloped glazing spanning 100 m^2 was not modelled at all: as assumed by the original modeller, it was an insignificant amount of area relative to the whole roof. Given more time and the skills to import new LCI datasets (proper EPD or use of SimaPro), I would have modelled this sloped glazing and aggregated its impacts in this Level 3 element.

A31 Inaccuracies

One key missing item in my analysis was structural drawing S1.1 (or a continuation of the foundation plan past gridline L). This was neither provided to the original modeller nor to me; therefore, I assume there was no further walls below grade past this gridline.

Similar to above cases, perimeter wall was modelled as "average" fly ash content while the minimum value from the structural drawings is 40%. This was remodelled as 35% fly ash input which is the closest match and modified in the inputs and model accordingly. If there were more time to complete this project, I would have attempted to find an EPD for a 40% fly ash mix and import the impacts.

A32 Inaccuracies

I did not have time to go through the elements of each curtain wall and tilt-up section and count windows, holes, etc. but given the poor quality and carelessness of the original modeller, given enough time, these values should be corroborated to confirm correctness

Concrete tilt-up wall was not even originally listed in the assumptions nor model but was in the OST file and the report. This was rectified by checking the takeoff, adding to inputs document, and modelling it in IE. The curtain wall was not checked due to time constraints.

B11 Inaccuracies

Again, due to time constraints, I did not have time to go through every element and every steel stud and check that the values were correct.

For cast-in-place concrete walls CW 4,5, and 6, the reinforcement type was modified to more accurately mimic conditions in the field. Given 15M vertical reinforcement and 20M horizontal reinforcement in the element where the 20M is at the same if not much tighter spacing, I remodelled all these elements as 20M reinforcement. This assumption makes sense as there will be more 20M reinforcement (in some elements twice as much) as 15M; therefore, modelling it as 20M is more conservative and accurate of field conditions than the original model of 15M.

As can be seen from the preceding synopsis of inaccuracies, this task required a huge time commitment and was impossible to complete in the time frame provided. Given less than 3 weeks to work on the final project upon issuance of the outline, it was not feasible to address every issue in the original model. With more time, a more accurate corroboration of each element value could be obtained as well as importing new LCI datasets.

Reference flows are the amount of products (in terms of inputs and outputs) per functional unit. So in the case of the activity performed in CIVL 498C on "Sphere and Airplane" production, the functional unit was distance travelled in steps by each vehicular means and the reference flow would be the amount of paper required to complete 1000 paces of travel. Reference flows provide a means to quantitatively assess each product's function

The following is the bill of materials for each of the CIQS Level 3 elements for the Kaiser building.

Table 8: Bill of Materials (Fred Kaiser Building) by CIQS Level 3 Element

CIQS Level 3 Element	Material	Quantity	Unit
A11 Foundations	Concrete 30 MPa (flyash 35%)	148.79	m3
	Rebar, Rod, Light Sections	1.98	Tonnes
A21 Lowest Floor Construction	6 mil Polyethylene	3,069.28	m2
	Concrete 30 MPa (flyash 35%)	303.80	m3
	Welded Wire Mesh / Ladder Wire	2.61	Tonnes
A22 Upper Floor Construction	Concrete 30 MPa (flyash 25%)	2,281.36	m3
	Concrete 30 MPa (flyash av)	2,415.42	m3
	Hollow Structural Steel	10.49	Tonnes
	Rebar, Rod, Light Sections	449.34	Tonnes
	Welded Wire Mesh / Ladder Wire	0.23	Tonnes
A23 Roof Construction	6 mil Polyethylene	2,863.09	m2
	Ballast (aggregate stone)	265,859.69	kg
	Concrete 30 MPa (flyash av)	956.05	m3
	Galvanized Sheet	1.00	Tonnes
	Glass Facer	5,667.89	m2
	Modified Bitumen membrane	23,852.10	kg
	Nails	0.01	Tonnes
	Polyethylene Filter Fabric	0.23	Tonnes
	Polyiso Foam Board (unfaced)	11,035.25	m2 (25mm)
	Rebar, Rod, Light Sections	50.21	Tonnes
	6 mil Polyethylene	2,863.09	m2
	Ballast (aggregate stone)	265,859.69	kg
	Concrete 30 MPa (flyash av)	956.05	m3

	Galvanized Sheet	1.00	Tonnes
	Glass Facer	5,667.89	m2
	Modified Bitumen membrane	23,852.10	kg
	Nails	0.01	Tonnes
	Polyethylene Filter Fabric	0.23	Tonnes
	Polyiso Foam Board (unfaced)	11,035.25	m2 (25mm)
	Rebar, Rod, Light Sections	50.21	Tonnes
A31 Walls below Grade	Concrete 30 MPa (flyash 35%)	166.61	m3
	Rebar, Rod, Light Sections	3.93	Tonnes
A32 Walls above Grade	Aluminum	44.27	Tonnes
	Concrete 30 MPa (flyash 35%)	69.46	m3
	Double Glazed Hard Coated Air	125.74	m2
	EPDM membrane (black, 60 mil)	791.38	kg
	Glazing Panel	109.10	Tonnes
	Nails	0.33	Tonnes
	Rebar, Rod, Light Sections	4.33	Tonnes
	Screws Nuts & Bolts	1.27	Tonnes
B11 Partitions	1/2" Regular Gypsum Board	238.70	m2
	5/8" Regular Gypsum Board	20,443.75	m2
	Concrete 30 MPa (flyash av)	134.66	m3
	Concrete Blocks	31,865.91	Blocks
	FG Batt R11-15	2,063.45	m2 (25mm)
	Galvanized Sheet	17.71	Tonnes
	Galvanized Studs	28.37	Tonnes
	Glazing Panel	0.38	Tonnes
	Joint Compound	20.64	Tonnes
	Mortar	608.42	m3
	Nails	0.69	Tonnes
	Paper Tape	0.24	Tonnes
	Rebar, Rod, Light Sections	154.17	Tonnes
	Screws Nuts & Bolts	1.57	Tonnes
	Small Dimension Softwood Lumber, kiln-dried	2.31	m3
	Softwood Plywood	1,815.32	m2 (9mm)
	Solvent Based Alkyd Paint	6.88	L
	Water Based Latex Paint	131.70	L

7.0 Communication of Assessment Results

Life Cycle Results

As discussed in prior sections, the building that I analyzed was the Fred Kaiser building on campus at UBC. It is fairly new construction that is used for mixed purposes: a large atria, research & study space, and offices for Engineering Student services are just some of these.

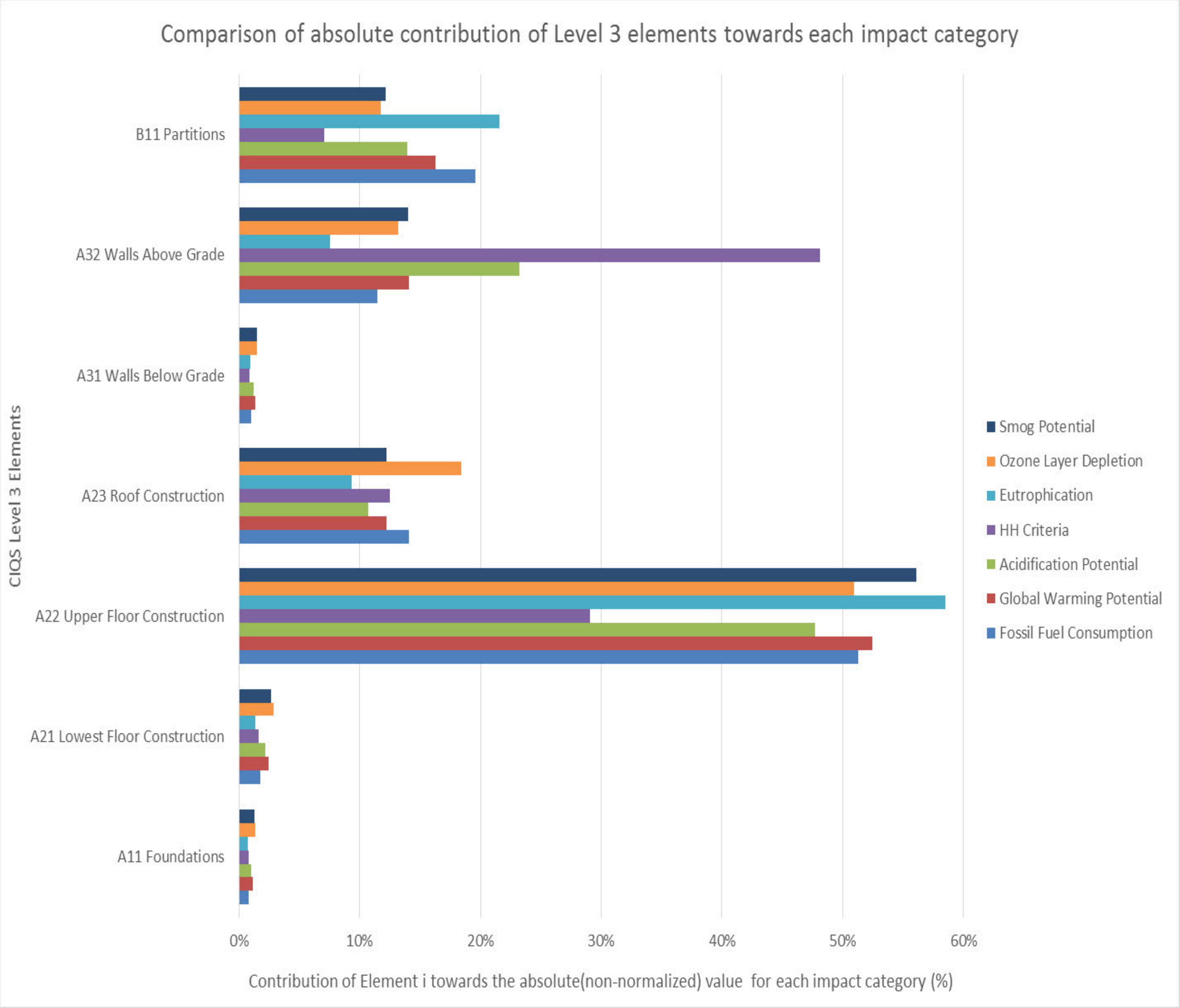
Table 9 displays the values for each category indicator and each CIQS level 3 element over all life cycle stages from cradle-to-grave. These are not absolute values but normalized values by dividing the total emissions for each impact category by the functional unit of that element. By themselves, these values mean very little, but in comparison with the benchmark, some meaning can be gleaned from them (see Annex A).

Table 9: Summary for each CIQS Level 3 element normalized by its functional unit

CIQS Level 3 Element for Kaiser	Fossil Fuel Consumption (MJ)	Global Warming (kg CO2eq)	Acidification (moles of H+eq)	Human Health Criteria – Respiratory (kg PM10eq)	Eutrophication (kg Neq)	Ozone Layer Depletion (kg CFC-11eq)	Smog (kg O3eq)
Whole Building	2,553.68	242.99	1.78	0.89	1.34E-01	1.11E-06	30.92
A11 Foundations	104.37	13.78	0.09	0.03	4.70E-03	7.36E-08	1.97
A21 Lowest Floor Construction	220.03	29.01	0.19	0.07	8.71E-03	1.54E-07	4.04
A22 Upper Floor Construction	1,646.35	160.24	1.06	0.33	9.84E-02	7.14E-07	21.77
A23 Roof Construction	1,748.64	144.91	0.93	0.55	6.11E-02	1.00E-06	18.39
A31 Walls Below Grade	649.01	80.82	0.53	0.20	3.14E-02	4.21E-07	11.41
A32 Walls Above Grade	1,066.20	124.58	1.50	1.57	3.70E-02	5.37E-07	15.77
B11 Partitions	579.45	45.95	0.29	0.07	3.34E-02	1.51441E-07	4.35

Figure 1 displays the percent contribution of each CIQS level 3 element towards an impact category, for all impact categories. Therefore, if you sum up all of the Level 3 element contributions for a given impact category their percentages will sum up to 100%: the whole building value. The values used in this are the non-normalized values because dividing by the functional unit, given that each element has different units, would lead to non-comparable results. From this figure, one can see that across all impact categories (except HH Criteria) that A22 Upper Floor Construction has over 50% of the total, absolute impacts for a given category. This makes sense, as A22 consists of all the upper floor slabs, beams, and columns which composes most of the structural system. In terms of HH Criteria, A32 Walls above Grade has the majority of the impacts. Given that A32 has a very different composition of materials (glazing and curtain wall) than other elements which are primarily concrete, a possible conclusion is that these products have more deleterious consequences towards HH Criteria.

Figure 1: Percent contribution of each CIQS Element towards the overall category indicator



Across all impact categories, the product stage contributes approximately 90% of the total for an impact category relative to the aggregate total of product and construction stage. This shows that in order to increase the sustainability of construction, a large focus needs to be placed on producers and manufacturers of products that feed into later life cycle stages.

In future projects, it would be an interesting and worthwhile exercise to see how these structural contributions towards these impact categories compares in a full LCA of the entire building (including HVAC, interior systems, tenant fit-outs, etc.) and usage. This would give a fuller picture of the life cycle from cradle-to-grave and understand the real percentage of impact of the structural system (our system boundary) relative to the whole building life cycle.

The following Annexes are supplements to the building declaration up to this point. They serve to further expound upon what has been discussed in this report and fill in information that would otherwise ruin the readability of this report.

Annex A presents the interpretation of results and explains the concept of benchmarking. The first part presents the methodology of benchmarking and importance of comparability between studies. The second part compares my building values against the aggregate benchmark compiled from all the LCA studies as a part of this project.

Annex B presents the recommendations for LCA use at UBC. It discusses the importance of all life cycle stages including use and decommissioning and outlines steps to operationalize LCA use at UBC.

Annex C presents the author reflection of this final project. The main topic of this author reflection is a critical review of the final project and the many shortcomings associated with it.

Annex D presents the pasted inputs and assumptions of the final model of the Fred Kaiser Building. In the attached document, sections highlighted in purple represent all the corrections I have made relative to the original modeller's work.

Annex E presents the data adjustments and substitutions example of substituting 25MPa concrete for 30MPa concrete into a wall assembly on impact estimator. It provides the series of excel inputs to achieve the final, modified profile of impacts.

Annex A - Interpretation of Assessment Results

Benchmark Development

Benchmarking in LCA is the goal of this course: it provides decision-makers the ability to logically interpret the vast amount of information that is the result of the individual LCA studies. In this course, the results for the different LCA studies were aggregated for 7 different impact categories. For each building, this was further subdivided for each CIQS Level 3 element as well as the whole building. These category indicators were then “benchmarked” by taking the arithmetic average across all buildings for each CIQS Level 3 element and each impact category. These benchmarks then state what the average environmental impact potential of UBC buildings is.

The benchmarks allow ease of comparison of individual buildings to the average to identify potential errors in modelling. If most buildings have similar designs and construction systems, yet the category indicators are differing by orders of magnitude, the benchmark system can quickly identify in which element and for what impact category there is a potential error.

The benchmarks serve as a decision tool for future designs. Planners and designers at UBC can see what past materials were used and the impact potential of these different elements across a multitude of buildings. This allows them to put real, tangible numbers into their decision-making and the ability to compare a proposed design to what the average benchmark is. Thus hypothetically, if UBC were aiming to reduce by 20% their impact of global warming potential of future construction, they could use these benchmark values to identify what current impacts are.

Common goal & scope and model development are important to ensure the studies being aggregated for the benchmark are indeed comparing impact potential in a fair and equitable way. For example, if one study included energy usage over differing service life, and one study didn’t include any envelope, there would obviously be no basis for comparison. By ensuring that each of the studies have a common goal & scope, all studies considered only the actual structure and envelope from “cradle-to-gate” (No “Use” or “End-of-Life” considerations) as well as following a similar sorting into CIQS Level 3 elements and functional unit per element. By having our class modify prior studies so that studies matched on all these levels, it ensures that aggregation and averaging of results does indeed have meaning.

In terms of functional equivalence of the benchmark, it also draws upon the argument from above: that aggregated studies must be similar in order to draw meaning from their results. Functional equivalence is the commonality of function and use between one product and another. In terms of whole buildings, all of our studies consisted of academic buildings located at the UBC Vancouver campus. This allows them to be readily compared as an industrial and academic building would obviously have very different systems and impacts, as would two similar used buildings but in different cities or countries. Further to this, functional units of square metres of slab-on-grade, floor area, or surface of wall were used (depending on the CIQS Level 3 element being examined). By using a common functional unit, one can define a unit rate which can easily be benchmarked (eg. X kilograms of CO2 equivalent per square metre of partition wall). Therefore, each level 3 element having a certain function (such as partition or wall below grade) has a corresponding functional unit which standardizes the impact potential based on quantity and use.

UBC Academic Building Benchmark

Given the importance of benchmarking outlined above, the following is a synopsis comparing life cycle impacts of various CIQS Level 3 elements and impact categories versus the benchmark.

The Figure 2 and Table 10 provides a snapshot of the percent differences between the benchmark of October 30th and the Fred Kaiser building model by CIQS Level 3 element and Impact Category. From this, it can easily be seen which elements of our model deviate largely, and for which impact categories, from the benchmark value. While the benchmark doesn't represent a "gold standard" that our model must obey, it provides a good reference to begin with to identify problematic Level 3 elements.

As can be seen from the figure and table, the Level 3 element in the Kaiser model which deviates the most from the benchmark is A11 Foundations. It consistently deviates by approximately 90% difference for every impact category which immediately looks like a "suspicious" result and requires closer examination. Based on prior sections of this report, this makes sense. There were many inconsistencies in the original modeller's foundation model (which I fixed to the best possible in the limited timeframe); however, the real problem most likely stems from the missing drawing S1.1 (Structural foundation plan beyond gridline L). This was provided to neither myself nor the original modeller so a whole section of the building's foundation system and slab-on-grade (SOG) would be missing from these values. In this way, both the impact potential (from non-modelled elements and their associated emissions) as well as the surface area of SOG (the normalization quantity and functional unit for foundations) would both be incorrect: a plausible reasoning for these erroneous results.

For elements such as A31 Walls below Grade, values across all impact categories are much more in line with the benchmark which would lead future student groups and analyzers not to focus on this element for improvements. The lower percent difference (as low as 2% for fossil fuel consumption) correlates to a higher likelihood that the model is indeed correct because it is similar to other construction on the campus which will inherently have similar standards and impacts.

Figure 2: Impact Category Percent Differences by Element between Kaiser and the Benchmark of October 30

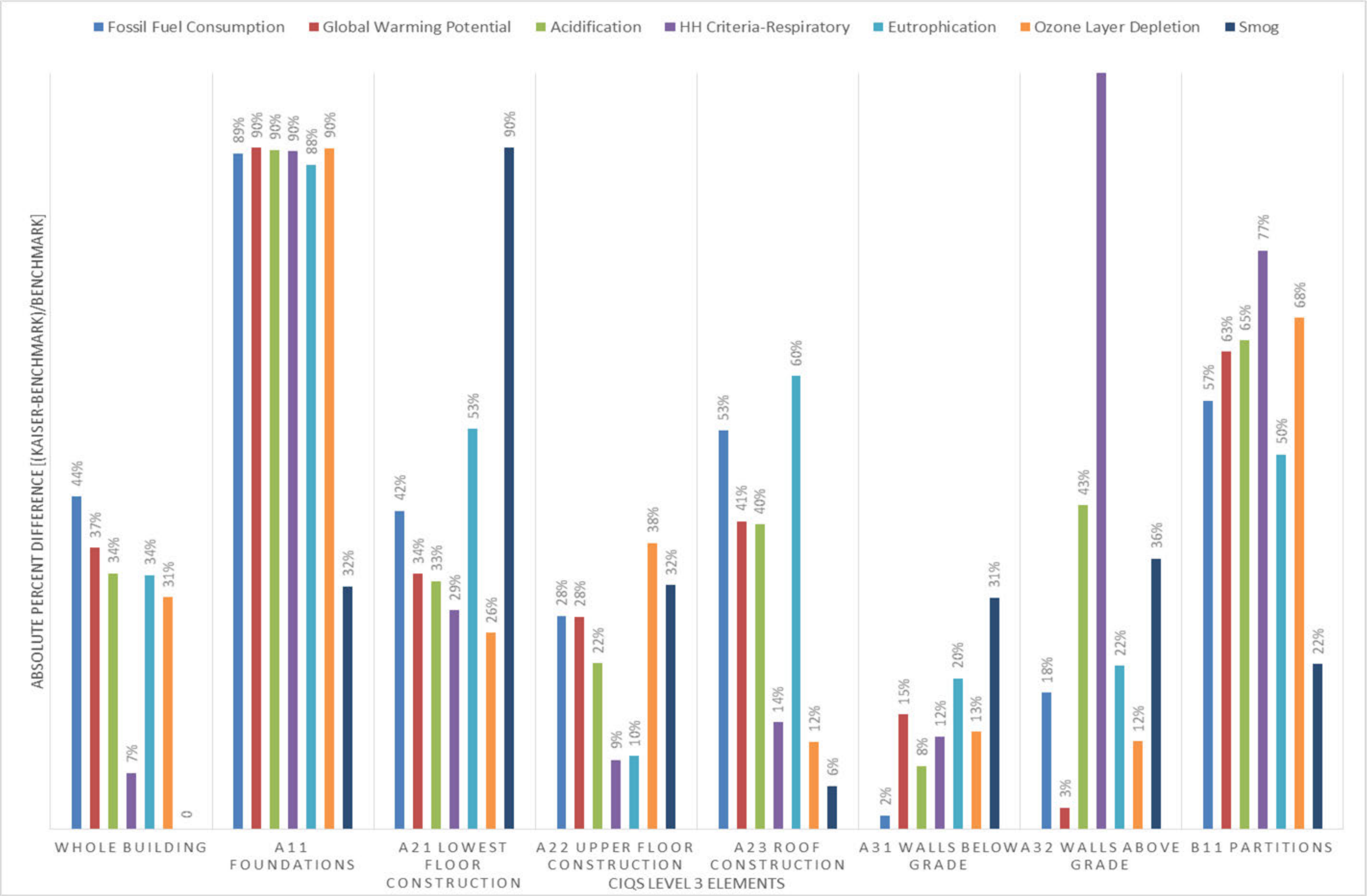
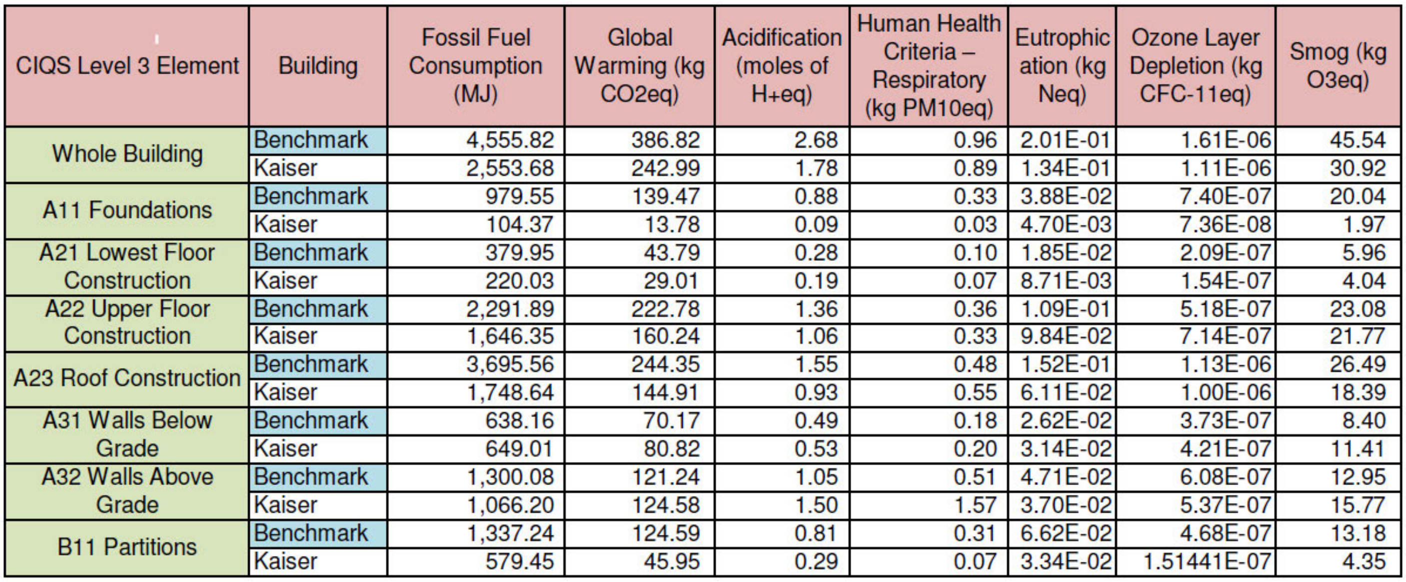


Table 10: Impact Potential of CIQS Level 3 Elements for Kaiser Building and the Benchmark



CIQS Level 3 Element	Building	Fossil Fuel Consumption (MJ)	Global Warming (kg CO2eq)	Acidification (moles of H+eq)	Human Health Criteria – Respiratory (kg PM10eq)	Eutrophication (kg Neq)	Ozone Layer Depletion (kg CFC-11eq)	Smog (kg O3eq)
Whole Building	Benchmark	4,555.82	386.82	2.68	0.96	2.01E-01	1.61E-06	45.54
	Kaiser	2,553.68	242.99	1.78	0.89	1.34E-01	1.11E-06	30.92
A11 Foundations	Benchmark	979.55	139.47	0.88	0.33	3.88E-02	7.40E-07	20.04
	Kaiser	104.37	13.78	0.09	0.03	4.70E-03	7.36E-08	1.97
A21 Lowest Floor Construction	Benchmark	379.95	43.79	0.28	0.10	1.85E-02	2.09E-07	5.96
	Kaiser	220.03	29.01	0.19	0.07	8.71E-03	1.54E-07	4.04
A22 Upper Floor Construction	Benchmark	2,291.89	222.78	1.36	0.36	1.09E-01	5.18E-07	23.08
	Kaiser	1,646.35	160.24	1.06	0.33	9.84E-02	7.14E-07	21.77
A23 Roof Construction	Benchmark	3,695.56	244.35	1.55	0.48	1.52E-01	1.13E-06	26.49
	Kaiser	1,748.64	144.91	0.93	0.55	6.11E-02	1.00E-06	18.39
A31 Walls Below Grade	Benchmark	638.16	70.17	0.49	0.18	2.62E-02	3.73E-07	8.40
	Kaiser	649.01	80.82	0.53	0.20	3.14E-02	4.21E-07	11.41
A32 Walls Above Grade	Benchmark	1,300.08	121.24	1.05	0.51	4.71E-02	6.08E-07	12.95
	Kaiser	1,066.20	124.58	1.50	1.57	3.70E-02	5.37E-07	15.77
B11 Partitions	Benchmark	1,337.24	124.59	0.81	0.31	6.62E-02	4.68E-07	13.18
	Kaiser	579.45	45.95	0.29	0.07	3.34E-02	1.51441E-07	4.35

Comparison of Cost versus Global Warming Potential

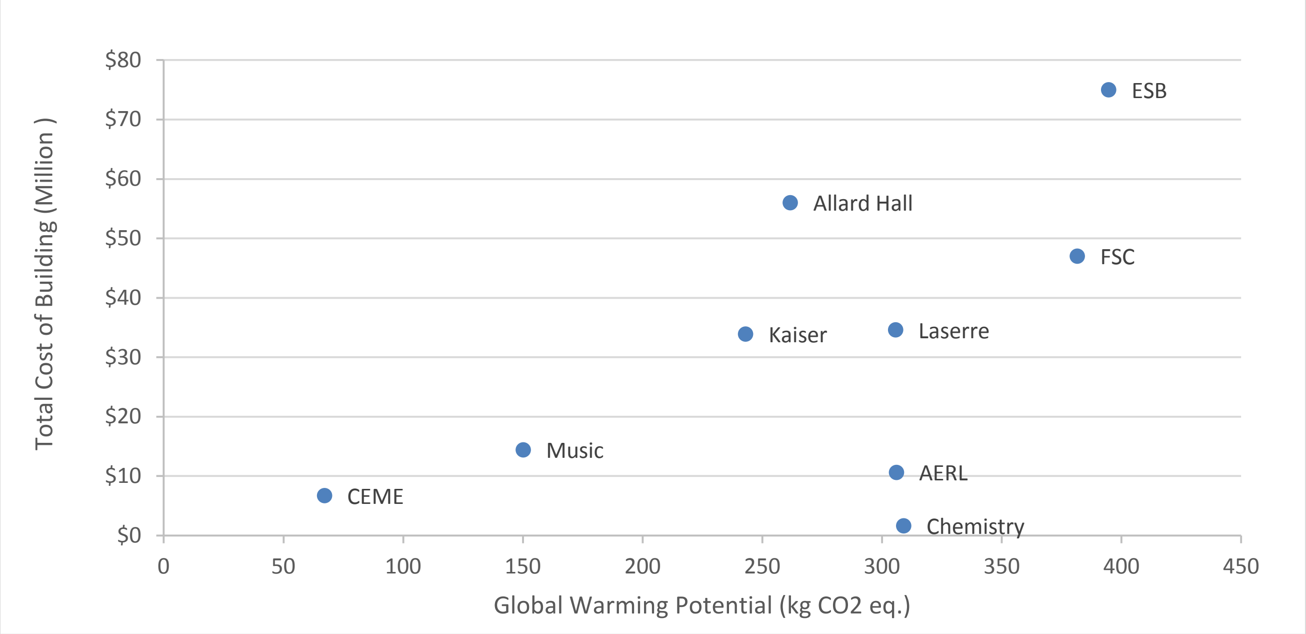
Global Warming Potential was the impact category identified by our class in the “Impact Aversion Survey” as the number one priority for ourselves. In this sense, the main item to be analyzed in the following is a plot of costs and global warming potential (GWP).

Figure 3 is a plot of total building cost versus global warming potential for buildings which are part of the UBC LCA project. These values were taken from the online course document (Google Drive Final Study Results) on November 14th. At this time, many people did not have their costs posted or erroneous values were in place: therefore, I only plotted the reasonable values on this plot. The GWP values represent a normalized GWP per square area of building while the cost is a total cost for the building. Ideally, I would have normalized these values, but at the time that I compiled this data, very few building areas were yet in the Google Drive file.

The cost represents the final cost required for completion and commissioning of the building (including finishes, HVAC systems, and all building components) while our studies only examined the embodied impacts of the structure and envelope and their upstream processes. This leads to a disparity between the cost and global warming potential relationship as the cost values are on a complete building basis while the GWP values are based on just the structural members and envelope.

This figure shows a clear, linear trend at UBC buildings between increasing cost and increasing global warming potential. While this is a trend that is not ideal (as expensive buildings also have high impacts), there are many reasons for this.

Figure 3: Global Warming Potential versus Cost for UBC Buildings



Firstly, the two buildings with the least global warming potential are two historically old buildings at UBC. Given the age of these buildings, the construction materials, processes, and designs are very different from more modern designs and levels of finishes. Given that Athena's LCI database models all of the emissions in terms of the current construction climate, the temporal variability between their construction timeframes and the current construction era could lead to high differences in values. This explains their low costs and impacts.

Secondly, it makes sense that as a building's costs escalate: typical precedent means that there is a higher level of finishes, quality, and "extravagance": all leading to higher impacts. In the case of the two highest impact buildings: they are both made of wood which has an extremely high cost relative to other materials, which manifests itself in this plot. This does seem rather strange, however, as wood is typically seen as a low GWP and low impact material relative to traditional concrete.

The results of Kaiser (excluding the extremely low value studies of CEME and Music building which appear erroneous) represents a low cost & low impact building relative to other modelled buildings. For example, Kaiser has about ½ of the GWP of the ESB and is also ½ of the cost: the best case from a design standpoint. This plot can be used to identify GWP of already constructed buildings for a given pricing to yield a benchmark GWP value from linear interpolation for future construction. For example, a $60M building on this plot would have approximately 375 kg CO2 equivalent per square metre of useable floor area in the building. From this value, UBC can then say that they want a proposed design to have 10% less GWP than this standard.

Annex B - Recommendations for LCA Use

The following section will outline recommendations for operationalizing LCA in building design.

From the start of any LCA study, a consistent and compatible goal & scope should be established. In the framework of the UBC Initiative to benchmark buildings and make future design decisions, the goal & scope of all new LCA studies on existing or new designs should be similar and compatible to the studies used in our benchmarks. This allows ease and validity of comparison.

Consideration of all modules throughout the building life cycle is a requirement of any thorough, meaningful study. The reason that our studies omitted modules beyond the Product and Construction Process module were due to time and knowledge constraints in this introductory course and due to the software restrictions and uncertainty. A whole, realistic portrait of environmental impacts can be envisioned if we consider the use and end-of-life stages of the building, which would account for the energy efficiency as well as recyclability of building materials: a huge flaw that our studies do not address. By omitting the use phases from a study, products may appear to have a larger impact potential in just the product and construction phase and be discounted. In reality, it may be extremely efficient throughout the design life of a building: giving a wrong perception about impact potential of a system and material.

Another consideration related to the above is matching products to the appropriate model in the Impact Estimator. If the analyzed product comes from a typical, normal manufacturing process, it is logical to use the provided LCI data. However, if your product comes from a "LEAN" manufacturing process, or an especially sustainable company, an environmental product declaration (EPD) or other LCI dataset should be imported into the model to appropriately account for this increase in efficiency. In the case of a building which uses extremely eco-conscious or efficient suppliers, a large discrepancy may exist between Impact Estimator pre-loaded datasets and the actual site conditions. This needs to be addressed to the best of the modeller's ability to closely match reality.

LCA can be managed from the point of high-level decision making to determine structural and envelope systems, as well as analyzing previous programming that leads to more environmentally-sustainable designs. By having an accessible benchmark, a designer can quickly look at previous designs of similar floor area and structure and determine the approximate impact potential. From this point, the designer can identify client and stakeholder concerns such as which impact categories are the most important, and tailor their design to address these needs. Given a benchmark which also addresses the process modules of use and end-of-life, a designer can make conclusions about the best materials to reduce the entire impacts over the lifespan of a building as opposed to just the construction impacts. This can serve as a method of justification for higher costs and labour expertise during construction in order to have a product which will perform more efficiently over a longer service life.

In operationalizing LCA, availability and quality of data is a crucial factor. Given that LCA is a model of real-life environmental impacts, poor inputs only lead to a completely false model of reality. As the computer engineering adage goes "junk in = junk out" and this could be no more true than for LCA. In saying this, a strong push in the industry over the coming years should be to aggregate better LCI datasets and benchmarks. For LCI datasets, modeller's should ensure that they are examining all possible options for LCI data and working at the forefront of the industry to increase openness. A benchmark separated by categories of building use (residential, academic, industrial) for a wide array of building useable square footage and environmental performance levels over the entire life cycle would give the best indication of performance. Having this large benchmark pool for each use would provide an accessible tool for all designers to have a set of data that is proven in industry: this ensures quality, real data.

Issues in application such as prioritizing impact categories can be addressed by conducting charettes and full stakeholder meetings to assess the environmental impact categories of concern on the project. By having open conversations early in the design process with clients, designers, and stakeholders to assess via survey or by discussion the greatest concerns: design decisions can be weighted to allocate resources to meet the greatest concerns.

<u>Steps to Operationalize LCA at UBC:</u>

If UBC wanted to operationalize an LCA program to centralize methods, data and use in practice on campus, I would propose the following based on my limited understanding of the issues.

Firstly, I would hire a working group on LCA to work in the UBC Planning or Sustainability Office who were dedicated to the promotion of sustainability in building planning and design on campus and constant improvement of current methods. From here, I would provide them our class benchmark and push for the continual broadening and refinement of the database. This could be done by having more iterations of building LCAs and critical reviews conducted to expand the breadth of the database. As more buildings are analyzed, the ability of one awry study to affect averages would be significantly reduced.

To further refine data collection for the LCI process, typical UBC contractors and suppliers could be forced to provide EPDs and other documentation to corroborate environmental claims and create an LCI database highly-tailored to UBC and its typical construction processes. As we learned in UBC's CIVL 400 course on construction management, "Projects at UBC take typically twice as long to get something done than anywhere else in Vancouver". If UBC's construction climate is really this different in terms of scheduling, maybe it is worth looking into the establishment of a tailored LCI database which better meets the needs of UBC construction than the Athena Impact Estimator for accuracy. This would allow constant refining and improvement of existing data sources, increasing the input accuracy to the model.

The next step would be to conduct campus-wide surveys of stakeholders on impact categories: to determine a weighting for what people want to mitigate in terms of environmental impacts. This benchmark could then be used to set targets at 10 year horizons for those which had the highest aversion score: such as "All new building construction on campus by 2025 needs to score 20% less than the current benchmark of all UBC buildings in terms of Global Warming Potential". This provides a quantitative metric that Campus Planning can enforce in the approval of new buildings and services. By having this metric, a more informed decision can be made, rather than just saying that “this building is very sustainable”.

Ultimately, UBC should mandate LCA studies in order to receive funding and/or permitting if they deem this to be an important criteria for determining sustainability of design. By mandating LCA and a higher level of sustainability in design, UBC can force industry to use this novel approach to construction planning and design by considering environmental impacts over the entire design life of a building from raw material extraction to decommissioning. Setting aggressive goals from the benchmark data for new construction in order to gain approval and requiring approval via independent LCA consultants will set a new standard for “green building design” on campus.

Annex C - Author Reflection

Prior to starting this course, I had no experience with LCA; however, there are many courses in my undergraduate degree which promote sustainability. In second year, CIVL 202 was a course dedicated to community service learning, system planning, and sustainability learning. In fourth year, CIVL 405 serves as an introduction to environmental impact assessments and features a number of lectures from professionals and guest speakers on topics ranging from eutrophication in lakes, phosphorous recovery and oil sands development.

In CIVL 498C, the course was dedicated purely to learning about LCA. Firstly, the founding standards for all LCA methodologies: ISO 14040 and 14044 were reviewed in class and definitions learned to understand more fully the basis and provide a guiding document of all LCA studies. Then, an introduction to the goal & scope process and the need for proper definition of studies was reviewed. In following weeks, the LCI process was explained and how this relates material and energy input flows from quantity take-offs of a structure to quantifiable environmental emissions to air, water and land. These LCI outputs then serve as inputs in the LCIA methodology: where LCI outputs of emissions are quantified by characterization factors into a base unit for different impact categories. In our studies, midpoint indicators quantifying the “potential” for certain phenomenon are the final output of an LCIA and then open to interpretation. All of these topics and my understanding are explained in more full depth throughout this report; therefore, a larger explanation is note provided within this section.

I chose to enrol in this course as competence in sustainability issues and environmental concerns are becoming a necessity for any engineer in the current societal climate. With pressing issues all concerning climate and the environment we are surrounded by, I felt that this course offered the potential to teach a lot about these areas. In terms of the final project, we were not really presented with its final form until the end of October so I had no preconceived notion of what it would be prior to starting this course. In enrolling for this course, I was hoping to have a more full experience of conducting my own LCA study as prior years had done.

I felt that this project had some strengths but a lot of weaknesses in the way that it was delivered. I am presenting these thoughts here in hopes that things can be improved for future years (in line with the CEAB attribute of professionalism and accountability).

Firstly, there were some strengths to this project. I completed a whole-level overhaul of a previous year's models and used many industry tools and software to perform take-offs and used the Athena Impact Estimator to quantify impact potential of my building, Fred Kaiser. Further to this, I helped to establish a benchmark and provided a lengthy document on my project as well as other LCA issues. The research component of this project allowed me to learn a lot about different LCA methodologies, EPDs, and the framework of the software we used. I now have a functional understanding of LCA and its associated highlights and pitfalls but this came with a lot of frustration in completing this project.

However, this project has been an extremely time-consuming and frustrating process: I will highlight the deficiencies and provide constructive criticism within in order to motivate future improvements.

Firstly, this project required an extremely heavy time commitment for the period in which it was assigned. We were only given the final outline of the deliverables and what was required on October 29th and the final project was due November 18th. This provided just under 3 weeks to complete all the deliverables as outlined on the course WikiSpace. This would be a reasonable project if the outline was proposed in the middle of September, however, with less than 3 weeks to complete this and balancing a full course load of engineering projects, this is completely unreasonable. I have had to spend minimal time on my other courses by providing over 8 hours a day for the last two weeks to this project just to create an acceptable quality report to meet all deliverables. When I had my meeting with Rob to discuss this course's progress, I clearly mentioned that the 4th year program of Civil Engineering is extremely project-intensive and all of our deliverables (which were outlined in September) are due at the same time. Even as of November 15th, we have still not been provided with how to conduct the net present value calculations: imperative to construct the final cost versus GWP plots and finish deliverables. In this sense, it has been an extremely frustrating process.

Secondly, I feel like the actual workload is more than the instructor expected for this project and should have been pared down. There is a large disparity between people's levels of effort required to complete this project. For example, the original modeller of my project did an extremely poor job on his model: he input data randomly, made up values for the IE, and completely carried out his methodology with no way to trace and follow his assumptions as highlighted within my report. This forced me to spend days of work just to make sense of what had occurred, and attempt to rectify the laziness and carelessness of the original modeller. A better format for the course, as Rob discussed in our lecture on November 13th, would have been to have us model the energy usage of different buildings, or use SimaPro to model phenomena outside of IE's capabilities. Work that did not wholly rely on the effort of others would have made for a lot more pleasing experience and learning in this course. In this sense, the problems of previous years would not be passed down to myself and require a large effort to repair with absolutely no payback. While the critical review process did impart some learning, I spent over 90% of my time on this project frustrated to understand an irrational methodology of modelling, missing assumptions, and missing information provided by the original modeller. This led to very little learning for myself per unit time spent on this project which is unfortunate as this elective could have offered a lot of potential. Also, a full set of drawings was missing in my project and should also be provided for completeness. Both the original modeller and I were missing the structural set of drawings for the Kaiser building beyond the first section of the foundation plan. It is extremely difficult to complete the coursework without the full information needing to be modelled.

In future years, my recommendations for this course are to provide a full, complete outline for the project at the beginning of the course and have a project independent of prior student’s effort or lack-thereof. I could have slowly worked on my project since September and slowly learned information over time as opposed to relegating priorities in other classes just to finish this project and having a decreased learning experience. I feel like this would have alleviated a lot of the stress and frustration accompanying this elective and make it an experience where one consistently feels like they are learning and improving, instead of pure frustration.

Table 11: CEAB Graduate Attributes for CIVL 498C Final Project

Graduate Attribute	Description	Select the content code most appropriate for each attribute from the dropdown menue	Comments on which of the CEAB graduate attributes you believe you had to demonstrate during 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	IDA = introduced, developed & applied	Learned about LCA and its methodology and applied to this project
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	Through personal work (outside of class) completed the project to meet the objectives outlined
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	Through personal work (outside of class) completed the project to meet the objectives outlined using software introduced in class
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	N/A = not applicable	Not covered
5 Use fo 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	A = applied	Through work and research on the final project (outside of class), learned the limitations of the software and to refine the original model
6 Individual and Team Work	An ability to work effectively as a member and leader in teams, preferably in a multi-disciplinary setting	N/A = not applicable	This was an individual project so there was no formal team or teamwork
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	A = applied	My report, which totals over 12,000 words , is a form of effective report meeting the instructions provided
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	N/A = not applicable	Not covered in this course
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	I = introduced	This was briefly discussed in the course (category indicators and their associated endpoint impacts) but was not a main focus of the course More content and involvement in the final project to take these category indicator values and quantify them to real impacts (eg is there a threshold above which kg SO2 causes acidification?) would be more helpful
10 Ethics and Equity	An ability to apply professional ethics, accountability, and equity	A = applied	I wrote an honest feedback of the course in Annex B-Author Reflection as a form of accountability in this course I found the project to be an overwhelming workload in the time provided and feel that this was a huge problem that needs to be addressed and changed
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	N/A = not applicable	Not covered in this course One lecture on Net Present Value but the lecture slides were never provided for use in the final project
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	A = applied	Taught myself how to use Athena IE, OnScreen TakeOff and find relevant references as this wasn't reviewed in the course

Annex D – Impact Estimator Inputs and Assumptions

Please see attached file labelled “Inputs and Assumptions” in the .pdf file (did not append correctly in Microsoft Word).

Annex E – Data Adjustments and Substitutions

Please see attached file labelled “Data Adjustments and Substitutions” in the .pdf file file (did not append correctly in Microsoft Word).