UBC EMBODIED CARBON PILOT

Study of life cycle assessment protocols and tools at the University of British Columbia

THE UNIVERSITY OF BRITISH COLUMBIA

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The report describes whole building life cylce assessments conducted on UBC buildings and analysis of the results for the Embodied Carbon Pilot, between April 2019 and March 2020.

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Athena Sustainable Materials Institute was an key partner in this pilot, providing valuable expertise and insight into the protocal and processes for LCAs. Additional, contributions from UBC Campus and Community Planning and from Dialog, provided key project information for the pilots.

Cover Image: Campus Energy Centre by Ema Peter, courtesy of Dialog

EXECUTIVE SUMMARY FINAL DRAFT

The UBC Embodied Carbon Pilot was the first phase of a multi-year research study to improve our understanding of the practice of conducting whole building life cycle assessments, and how it can be used to inform policy and guidelines on embodied carbon emission from building materials, through the establishment of benchmarks and eventually performance targets. It was conducted by the Urban Innovation Research team in the UBC Sustainability Initiative, in collaboration with UBC Campus and Community Planning and Athena Sustainable Materials Institute, and supported by funding from Forestry Innovation Investment's Wood First program.

The building industry is a significant contributor to climate change. Buildings and construction are currently responsible for 39% of all global greenhouse gas (GHG) emissions (UNE 2017), and since the rate of construction is only expected to grow in the coming decades, reducing emissions from the building sector is critical to addressing climate change. GHG emissions from the operation of buildings have been most significant, but as buildings' operational energy consumption is reduced, along with the associated operational emissions, the embodied emission from building materials choices are becoming proportionally more significant.

Embodied carbon emissions refer to the GHG emissions attributed to materials throughout their life cycle. It can be calculated through a life cycle assessment (LCA), a scientific approach and framework to quantify potential environmental impacts from cradle-to-grave (e.g. extraction, production, installation, use, and end of life), and used to inform design and procurement decision-making. In LCA, embodied carbon emissions are referred to as Global Warming Potential (GWP) and reported in kilograms of equivalent carbon dioxide (kg CO2 eq.). Increasingly, as policy-makers are targeting embodied carbon emission from buildings, they are requesting that project teams use LCA tools to estimate and report the GWP of their designs.

A whole building life cycle assessment (WBLCA) entails a comprehensive environmental impact assessment of the major components of an entire building, over its life cycle. A WBLCA can be done at any stage of design based on project documents. However, one conducted towards the end of design development based on construction documents will be the most representative of the actual GWP impacts of the building. The WBLCA uses a project bill of materials (BoM), an accounting of the specific types of materials and their quantities used in the building that is generated from 2D drawings or 3D models. The BoM is mapped to the materials library of an LCA tool, in an online or software application, which then calculates the environmental impacts of the material quantities based on internal algorithms. There are many different LCA tools, each with their own particular properties. Three of the most common tools in North America, as related to embodied carbon, are Athena Impacts Estimator for Buildings, Once Click CLA and the Embodied Carbon in Construction Calculator (EC3).

The UBC Embodied Carbon Pilot leverages UBC's Campus as a Living Lab initiative, which enables the buildings and infrastructure of the campus to be a source of research and learning, to study the embodied carbon emissions of buildings. We conducted nine WBLCAs on three campus buildings: First Nations Longhouse, Bioenergy Research and Demonstration Facility (BRDF), and Campus Energy Centre (CEC). The scope of the WBLCAs focused on major building components – foundation, structure and envelope – which are the most significant contributors of embodied carbon emissions.

The Pilot focused primarily on the CEC, a hybrid mass timber building housing the hot water boiler system for the academic district energy system, completed in 2015. Using project documentation provided by the architect, Dialog, we conducted five WBLCAs using Athena Impact Estimator (Athena IE), and two WBLCAs using other tools (One Click LCA and EC3). The assessments are based on

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progressive stages of design development to allow for comparison of the different levels of project detail and the resulting GWP impacts. These assessments were based on BoMs exported from a preliminary 3D BIM model, BoMs developed by a professional consultant for costs estimates at 50% and 85% design development, and BoMs created from material quantities takeoffs from Issued-for-Constriction (IFC) and Record Drawings. We also compared the three different LCA tools listed above, using the BoM from the IFC Drawings, to explore the variations between the tools and resulting GWP impacts. All of these assessment are described in Section 2.

We compared the BoMs and assessments results to examine the impacts of the different project data sources – including construction drawings, a BIM model and design cost estimates – on the GWP results and the impacts of the different LCA tools on the GWP results, which are described Section 3. Throughout the pilot we also documented the processes, assumptions, and issues that we encountered to better understand the challenges and tradeoffs in conducting WBLCAs. In addition, we tracked work hours to analyze the breakdown of tasks and the correlation between people hours, data sources and the results. This also included a preliminary review of an existing design-phase LCA conducted by consultant for the project team during the design of the CEC, to understand how our assessments compared with theirs.

We found that there was significant variation in the CEC's BoMs from the different project data sources, both in terms of the list of materials and their respective quantities. In some cases, the variation reflected the refinement of the project design and the greater amount of detail. For example, the BoM from the 85% cost estimate had a larger list of materials than the BoM from the 50% design estimate. Other variations were due to assumptions made within the LCA tool based on standard building assembly information, as compared to the actual project information. These variations translated into differences in the total GWP impacts, as well as the proportional breakdowns by building element (e.g. foundations, beams and columns, floors, exterior walls and roof).

The breakdown by life cycles stage was largely consistent, with the product stages as the most significant by far, followed by the use stage (maintenance and replacement), and to a lesser degree, construction and end of life. Since two of the primary elements in the CEC are mass timber and steel, the external benefits beyond the life of the building (i.e. potential positive offset of the impacts through carbon sequestration and metals recycling) were significant. Depending on the assessment, the 'saved' GWP impacts from these benefits could offset about half (between 39% and 57%) of the total GWP impacts of the building.

The research and experience from the Embodied Carbon Pilot provide a better understanding of the challenges, trade-offs and information gaps in developing accurate BoMs and the effect that has on the resulting GWP impacts. These insights are is discussed in Section 4, along with a preliminary set of recommendation for policies on the use of WBCLA to inform embodied carbon benchmarks, and guide-lines to assist project teams in navigating the process.

We are building on the work described in this report with a second phase of the Embodied Carbon Pilot. We intend to conduct WBLCAs on a selection of mid-rise, multi-unit residential buildings, a common building typology in B.C. This research will follow the protocols we have developed in Phase 1, to further explore the effects of project data source and BoMs on the variation of results, and the intersection of GWP impacts with life cycle stages, building elements and materials choices. The Embodied Carbon Pilot Phase 2 will continue to inform policy and guidelines in using WBLCA to establish benchmarks and eventually performance targets for embodied carbon in buildings.

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LIST OF ABBREVIATIONS

Athena IE | Athena Impact Estimator for Buildings

BIM | Building Information Modelling

BoM | Bill of Materials

BRDF | Biodenergy Research and Demonstration Facility

CEC | Campus Energy Centre

CLT| Cross Laminated Timber

CO2 | Carbon Dioxide

EC3 | Embodied Carbon Construction Calculator

EPD | Environmental Product Declaration

GLT| Glue Laminated Timber

IFC | Issued For Construction

IFT | Issued For Tender

LCA | Life Cycle Assessment

Longhouse | First Nations Longhouse

GWP | Global Warming Potential

UBC | University of British Columbia

WBLCA | Whole-building Life Cycle Assessment

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GLOSSARY OF TERMS

Bill of Materials | a summary of the estimated quantity of materials required to construct the building, which does not typically include waste material which is a bi-product of construction.

Embodied Carbon Emissions | the GHG emissions, measure in equivalence to CO2, from the assocaited with materils and products (as opposed to emissions from operations).

Environmental Impact Category | environmental impact issue being examined. e.i. Global Warming, being measured by global warming potential (GWP).

Environmental Product Declaration | a third party verified report providing quantified environmental data (impacts) using predetermined parameters and, where relevant, additional environmental information for the product being studied.

Greenhouse Gases | emissions are those that trap heat in the Earth's atmosphere. Commonly these are carbon dioxide, methane, nitrous oxide, and fluorinated gases (such as CFCs, HCFCs, and HFCs found in refrigerants).

Life Cycle | consecutive and interlinked stages of a product from raw material acquisition or generation of natural resources to the final disposal.

Life Cycle Assessment | compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its life cycle.

Object of Assessment | defines which materials and componetns are included in the scope of the LCA.

System Boundary | describes what is being assessed within the life cycle of the system studied.

Whole Building Life Cycle Assessment | compilation and evaluation of the inputs, outputs and the potential environmental impacts of an entire building throughout its life cycle.

SECTION 1.0: INTRODUCTION

1.1 BACKGROUND AND OBJECTIVE

The impacts of a rapidly changing climate, caused by rising levels of greenhouse gases (GHG) are being felt around the world. The building industry is a significant contributor. Building and construction are responsible for 39% of all global emissions, with operational emissions are estimated to account for 28%, and the manufacture and construction of building materials for 11%.Reducing the emissions from the building sector is critical to addressing climate change, especially since the rate of construction is only expected to grow: the UN estimates that the world will build 230 billion square meters of new construction by 2057 (UN Environment and International Energy Agency, 2017).

Currently, GHG emissions from the operation and use of buildings comprise the largest portion of the total emissions from the building sector. Through advancements in technology, design and regulations, however, the industry is starting to address buildings' operational energy consumption, along with the associated operational emissions. As the operational emissions are reduced, the embodied emissions from building material choices are becoming proportionally more significant. Additionally, building materials choices have an immediate environmental impact at the time of their production and construction, so the reduction of embodied emissions provides a direct benefit in responding to the climate change emergency.

The University of British Columbia (UBC) has been at the forefront of sustainability for the last 30 years, including setting ambitious policy targets for carbon emissions from campus operations, and, in 2019, declaring a climate change emergency which recognizes the urgency in our efforts to mitigate climate change. To complement operational emissions targets, UBC's Green Building Action Plan has identified as a priority action the creation of regulations to reduce embodied carbon in buildings. This is a multi-step process, which includes understanding the embodied carbon emission from the existing building to establish first benchmarks and then performance targets for new buildings and major retrofits.

The Embodied Carbon Pilot, Phase 1, conducted by UBC Sustainability Initiative (USI), is one of the first steps in this process. The Pilot leverages UBC's Campus as a Living Lab initiative, which enables the buildings and infrastructure of the campus to be a source of research and learning, to study the embodied carbon emissions of campus buildings. We conducted life cycle assessments (LCA) of the major components of three campus buildings, which include the foundation, structure, and envelope. These components provide most of the embodied emissions from building materials. Additionally, we assessed the process of conducting LCAs themselves to gain an understanding of the procedural challenges and constraints since new reporting and compliance requirements must not add an unreasonable burden to project teams.

The Pilot focused primarily on the Campus Energy Centre (CEC), a recently completed mass timber building housing a state-of-the-art hot water boiler system that produces thermal energy for the Vancouver Campus. For the CEC, we conducted LCAs based on progressive stages of design development and construction documentation provided by the architect, Dialog, in order to study the variations in results as the project design was completed. We also conducted LCA, based on the same projct documentation, using three different online LCA tools to explore the variations in input data, protocols and results between tools: Athena Impact Estimator (IE), One Click LCA, and Embodied Carbon in Construction Calculator (EC3).

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For the Pilot, USI partnered with the Athena Sustainability Materials Institute, which allowed us to draw on Athena's expert guidance throughout the Pilot, as well as their knowledge of the intricacy of LCA tools and databases. USI also partnered with UBC Campus and Community Planning (UBC-CCP), who provided expertise in policy development, information gaps, and internal priorities around addressing embodied carbon emissions. Both of these organizations are primary audiences for this report outlining the learnings of the Embodied Carbon Pilot, which will be used to help inform policy development and guidelines for embodied carbon assessment, benchmarks, and eventually performance targets.

1.2 LIFE CYCLE ASSESSMENT (LCA) FOR BUILDINGS

1.2.1 Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a scientific framework that can be used to quantify potential environmental impacts of products as a performance outcome of design, manufacturing, use and end of life choices. A product's life cycle stages span across resource extraction, manufacturing/production, transportation, assembly/construction, use (including maintenance and renewal), and deconstruction (and disposal). The above method, known as a cradle-to-grave assessment, can be complemented with the benefits of reusing, recycling and recovering materials beyond the product's lifecycle, which is known as a cradle-to-cradle assessment (see Figure 1).

Figure 1: Flow diagram illustrating both clife cylce of a building

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For any LCA, it is critical to define the specific scope. Most modern products are complex assemblies of different materials and components, brought together through multiple global supply chains. As a result, it is important to be clear about the limitations of the LCA. There are two primary considerations when establishing the scopes of an LCA:

- The *object of assessment* defines which materials/components are to be included; and
- The *assessment system boundary* defines which of the life cycle stages are to be included (Athena Sustainable Materials Institute, 2014).

Most LCA methodologies, tools and standards provide guidelines for determining both the object of assessment and the assessment systems boundary.

1.2.2 Environmental impact categories and embodied carbon

Generally, the results of an LCA are reported in environmental impact categories. Different impact categories measure factors that could contribute to the restoration or degradation of regional or global ecosystems, waterways, finite resources, climate, and human health. The most commonly used environmental impact categories are: *Ozone Depletion Potential, Acidification Potential of Land and Water, Eutrophication Potential, Formation Potential of Tropospheric Ozone Photochemical Oxidants (Smog Potential), Non-Renewable Energy Consumption*, and *Global Warming Potential*. The overarching objective of an LCA is to quantify estimated impacts each of the categories. This information can be used to inform decisions aimed at reducing specific impacts or multiple impacts, to improve the ecological footprint of the product.

Embodied carbon is named after carbon dioxide (CO2) but refers to the emission of greenhouse gases (GHGs) into the Earth's atmosphere. Concentrations of GHGs retain thermal energy and lead to an increase in the average temperature of the Earth's climate system, referred to as global warming, which results in climate change. Different GHG compounds have different specific contributions to global warming and for LCA accounting purposes are simplified into a measurement of carbon dioxide equivalent generally reported in kilograms (kg CO2 eq.) in the environmental impact category of Global Warming Potential (GWP).

1.2.3 Whole building life cycle assessment (WBLCA)

A whole-building life cycle assessment (WBLCA) entails a comprehensive environmental impact assessment of an entire building, as opposed to only an individual component or product. The WBLCA process allows project teams and stakeholders to better understand both the totality of the environmental impact of the building and the contributions of major assemblies and components. The five life cycle stages of products in the generic LCA framework are further expanded in a WBLCA framework to add subcategories to each stage, as shown in Figure 2, which are common to nearly all building construction projects (European Committee for Standardization, 2011).

If a WBLCA is conducted during a project's design development phase, the results can be used by the project team to inform design decisions. Typically, design-phase WBLCAs focus on major building elements such as structure, foundations, and envelopes, and compare different choices, e.g. mass-timber vs. concrete superstructure. WBLCAs may also be used by policy-makers to inform policy benchmarks,

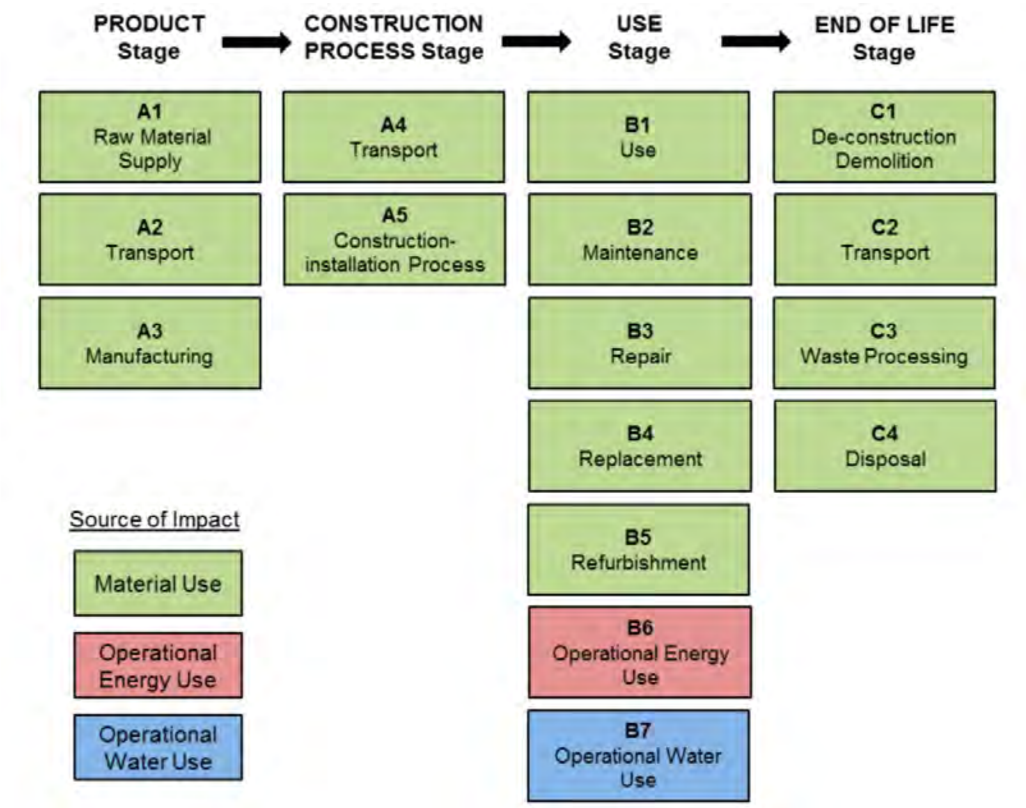

Figure 2: Stages contributing to the embodied carbon impacts over the life cycle of a building (Source: European Committee for Standardization, 2011).

targets, and regulatory standards. For these purposes, it is preferable to conduct a WBLCA on a complete building, using information from construction-phase documents, which provide the greatest details that most closely reflect the actual building. The results from WBLCAs of multiple buildings can be used to help inform appropriate benchmarks for different building typologies, set performance targets for future building construction projects, and be incorporated into green building standards.

Embodied carbon assessments through WBLCA are a way to understand and quantify the GHG emissions that are associated with building materials through material selection and construction methods. Generally, embodied carbon assessments include all of a building's life cycle stages except for operational uses.

1.2.4 BoM guidelines for benchmarking embodied carbon

The Athena Sustainable Materials Institute is currently developing new guidelines and protocols to create benchmarks for GWP (embodied carbon emissions), and eventually other impact categories. Towards this end, Athena is developing guidelines for establishing baselines and benchmarks using WBLCAs based on a building's Bill of Materials (BoM). A BoM is the list of the specific materials used in a building and their quantities. In current practice, it is typically used as a basis for detailed construction

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cost estimates, but may also be used for design and construction planning. The BoM is the main input from users to the LCA tools and is especially critical in understanding the embodied environmental impacts of building materials, such as embodied carbon emissions.

Athena's approach aims to address the challenges of comparability between WBLCA for different buildings. Since building projects are unique, it is difficult to compare the results from the WBLCA, as the object of assessments will vary with the differences in building type, design, size, procurement, etc., as well as the availability of data and assumptions made in the work LCA consultant. For the same reasons, it is difficult to create a consistent 'reference' building to use as a baseline from which to compare the performance of a design or as a benchmark for policy targets.

Instead, the BoM-based approach seeks to develop a standardized scope for creating buildings' BoM, based on high-quality data. Athena's approach uses the OmniClass classification system to standardize the way the material quantity takeoffs–the process of measuring material quantities, in area or volume, based on project drawings or models–are conducted and reported. OmniClass is a realatively new and comprehensive classification system for the construction industry that incorporates the other extant systems currently in use: MasterFormat, which mostly used to organize construction data and cost by trades, and UniFormat, which is mainly used for classifying building material quantifications and

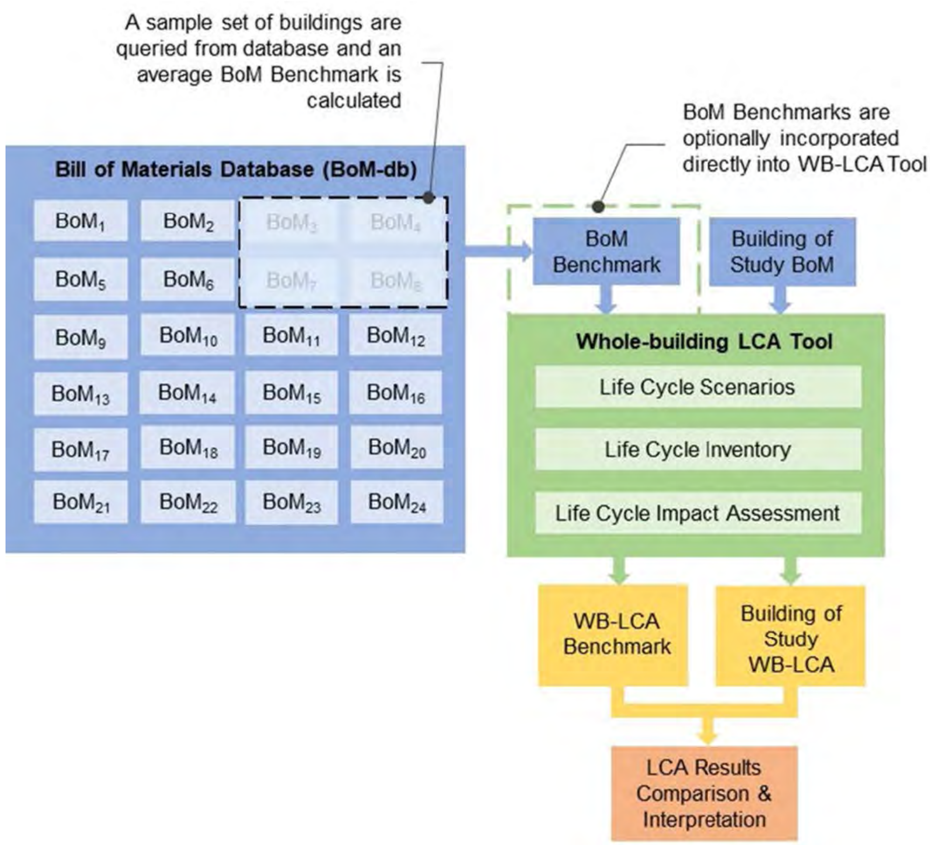

Figure 3: Sampling the BoM to create a benchmark for a proposed building of study (Source: Athena 2020)

cost estimation during design development.However, the most common classification standard that is currently used by quantity surveyors and LCA tools is UniFormat. Therefore in this Pilot study, we collected and organized material quantity information in UniFormat.

When sufficient data on existing buildings is compiled, using a consistent method, it will be possible to develop statistically-derived peer buildings to serve as a reference, based on materials quantities from relevant real buildings and scaled to the size of the proposed buildings, see Figure 3. This is part of a larger effort to develop a BoM database for Canada, as well as standard practices and guidelines for conducting WBLCA to create a more consistent approach across the industry (Athena Sustainable Materials Institute, 2020).

1.3 METHODLOGY

1.3.1 Overview of assessments

As noted above, USI was guided by Athena's approach to conducting WBLCA by developing detailed and accurate BoMs. Broadly this involved the following steps: selecting a shortlist of building on campus to use as pilots; collecting project documentation; generating LCA input information, in the form of BoM and elements assembly information, from the project documentation; organizing the BoM information and running the LCA; and analyzing the outputs. We also assessed different LCA tools and conducted a process-based analysis of the time and effort required for each approach.

In total, the team conducted ten assessments on three buildings, using varied project documentation/ LCA input and different LCA tools, as shown in Table 1. These assessments are described in detail in Section 2. The rest of this section describes our methods in data collection, LCA and analysis.

Data source *LCA Tool*	First Nations Longhouse	Bioenergy Research and Demonstration Facility	Campus Energy Centre
Assembly Method *Athena IE*			Assessment 3
BIM model *Athena IE*			Assessment 4
Cost Estimates *Athena IE*		Assessment 2	Assessment 5 (50%) Assessment 6 (85%)
IFC Drawings *Athena IE*	Assessment 1		Assessment 7
IFC Drawings *EC3*			Assessment 8
IFC Drawings *One Click LCA*			Assessment 9

Table 1: LCA Pilots on three different UBC buildings, using various project documentation and different LCA tools.

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1.3.2 Building selection and data collection

Since this research project was intended to be exploratory, with input from UBC-CCP,we selected a shortlist of buildings with different functions, sizes and designs, as well as different consultant teams. Initially, we selected six UBC buildings: the Bioenergy Research and Demonstration Facility (BRDF), the Campus Energy Centre , the Baseball Indoor Training Centre, the Engineering Student Centre, the First Nations Longhouse, and the Orchard Commons student residence.

The first four of these buildings have mass-timber structures and are relatively small and simple in terms of design. They were also completed within the last 8-years, which was an important factor in compiling project information to perform the WBLCAs. The First Nations Longhouse was chosen because it is a unique building for the campus, featuring a heavy timber structure and aspects of traditional First Nations design. In addition, the LCA was of particular interest to UBC-CCP. The Orchard Commons student residence is a concrete high-rise with mass-timber features. It was chosen as a potential follow-up to the WBLCAs of other UBC student residence towers: Brock Commons Tallwood House and Ponderosa Commons Cedar House, completed in 2017.

Ideally, we would have been able to collect construction cost estimates with a detailed BoM for each building. However, UBC manages project costs in a specific manner that does not typically include the production of a construction cost estimate using quantity surveying. We, therefore, sought to collect an array of project documentation from UBC Records, as well as the primary consultants from each building, to generate the BoM:

- Architectural and structural drawings, either Record Drawings, Issued-for-Construction (IFC) documents, or Issued-for-Tender (IFT) documents.
- Cost estimates with material quantities calculated at different project stages.
- BIM or 3D virtual models.
- Existing LCAs done by the project team or their consultants.

Not all the information was available for each building project. Table 2 shows the sources of information successfully collected for each building. The availability of good quality information was the primary limiting factor in conducting the WBLCAs efficiently. After preliminary studies on the First Nations Longhouse and BRDF, we focused on the Campus Energy Centre (CEC), since we were able to collect multiple data sources from different design stages. Additionally, the architect of record, Dialog, was interested in sharing their documentation and experiences, which allowed more in-depth analysis and interpretation of the results. Due to time constraints, we did not proceed with the other buildings.

1.3.3 LCA inputs and assessment methods comparison

For the First Nations Longhouse, the BoM was developed from quantity takeoffs using the IFT drawings. Since the project dates from the mid-1990s, most of the drawings were done by hand, and the research team measured the PDFs using Bluebeam Revu software and calculated the BoM manually. We also conducted an LCA through the Assembly-method in the Athena IE tool using the materials and geometry from the IFT drawings to assign assembly categories for the components of a selected exterior wall.

Data Sources	First Nations Longhouse	Bioenergy Research and Demonstration Facility	Campus Energy Centre	Orchard Commons	Baseball Training Centre	Engineering Student Centre
Project Drawings	IFT (Architectural only)	IFC	IFC	IFC	IFC	IFC
Cost Estimates		Preliminary Design Devel-opment	50% & 85% Design Development			
BIM Model			Partial (~80% Design Development)			
Existing LCAs			Structural Elements			

Table 2: Project data collected on the six selected UBC buildings.

For the BRDF, the BoM was extracted from a preliminary cost estimate which was completed when the project design team was confirming the decision to use a mass timber structure. Since this was early in the design phase, the cost estimate only included a preliminary estimate of material quantities from major components. While the research team collected IFC drawings, due to time constraints, we did not pursue a detailed WBLCA for BRDF after the decision was made to focus on the CEC.

For the CEC, the research team collected multiple data sources from different stages of the project design process, including a partial 3D BIM model, cost estimates and the IFC and Record drawings. We created four different BoMs based on quantity takeoffs from the IFC and Record drawings, material quantities from the cost estimates created at 50% and 85% design development, and quantity takeoffs from the partial BIM model (an architectural and structural AutoCad Revit model created around 80% design development). Additionally, we used the BIM model to generate materials and geometric information to assign assemblies for major building elements, as input into an Assembly-method LCA.

1.3.4 LCA tools comparison

The most commonly used LCA tools in Canada are the Athena Impact Estimator for Buildings (Athena IE), One Click LCA, and Embodied Carbon in Construction Calculator. The assessment on the Longhouse and BRDF were done using Athena IE, as were most of the assessments on the CEC. After the research team decided to focus on a single building, we were interested in understanding the differences between the tools. Howexer, we also conducted LCAs of the CEC using each of the three tools, all based on the same BoM from the IFC and Record drawings, to identify variations in data inputs, user experience, and reported results to examine how the tools calculate the embodied carbon emissions.

Athena Impacts Estimator for Buildings (version 5.4): Athena Sustainable Materials Institute's Impact Estimator for Buildings (Athena IE) is currently one of the most commonly used LCA tools in North America. It draws on an in-house Canada-wide Life Cycle Inventory (LCI) database with about 200 construction materials. The tool supports the BoM approach by allowing users to import BoM information directly from Excel files. The software also has a database of preloaded building assemblies which can be used to estimate building materials via the Assembly method (Athena Sustainable Materials Institute & Morrison Hershfield, 2020).

One Click LCA (Database version 7.6): One Click LCA is an online tool developed by Bionova Ltd. for the European market and has recently been adapted to North America. The tool relies on publicly available manufacturer specific Environmental Product Declarations (EPDs) which can be used for comparison of product environmental impact and some in-house data and methods to fill the local EPD and other LCI data gaps. The calculation of a WBCLA in this tool is essentially a compilation of product information from EPDs (Bionova Ltd., 2020).

Embodied Carbon in Construction Calculator (version v-22.1.1_b-1302): Embodied Carbon in Construction Calculator (EC3) is a new open-source online tool supported by the Carbon Leadership Forum and conceived by Skanska USA and C Change Labs. The tool is focused on supply chain liability and specifically targets embodied carbon emissions from the production of building materials. Similar to One Click LCA, the tool uses materials quantities from project documents and draws on a database of EPDs, with a focus on significantly growing the product-based EPDs rather than the industry-average EPDs (Carbon Leadership Forum, 2020).

1.3.5 Pilot WBLCA scope

The scope of the WBLCA pilots focused on major elements and was kept consistent across all the pilots, as much as possible. The WBLCA's object of assessment was limited to the building's foundation, structure (including floor, roof construction, and load-bearing walls), and envelope (including exterior walls and roof). Previous WBLCAs on other UBC projects have shown that these elements constitute the majority of the building's materials as well as a considerable percentage of the embodied carbon of a building, and are therefore the most useful in terms of benchmarking and impact reduction. They are also highly likely to be assessed in design-phase WBLCAs as the structure and envelope are two of the major design decisions made in early design by project teams.

Within these major elements, connection details and other minor elements that were both too small and too complex to quantify were excluded. Additionally, we excluded specific elements that lacked sufficient information within the construction documents to quantify their material components. The specifics of each pilot LCA is described in the assessments in Section 2.

The assessment system boundaries used in the pilots included all life cycle stages which were possible in the LCA tools used to conduct the WBLCAs. As noted above, Athena IE was the primary tool used in the pilots. In Athena IE, the system boundaries are referred to as LCA modules and are detailed in Table 3. Operational energy and water use were excluded from the scope of theses pilots since the objective was to assess the embodied carbon in the buildings' materials.

The assessment system boundaries for One Click LCA and EC3 were slightly different. Since EC3 relies on their database of EPDs, which mainly contain information sourced from product manufacturers, the tool only estimates material impacts from the product lifecycle stage (A1-A3 in the Table 3 and in Figure 2). The assessment system boundary is not the full life cycle of a building since the majority of EPDs do not include information on transportation, construction, use, or end-of-life stages. One Click

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Information Module	Processes Included
A1 Raw material supply	Primary resource harvesting and mining
A2 Transport	All transportation of materials up to manufacturing plant gate
A3 Manufacturing	Manufacture of raw materials into products
A4 Transport	Transportation of materials from manufacturing plant to site, and construction equipment to site
A5 Construction-installation process	Construction equipment energy use, and A1-A4, C1, C2, C4 effects of construction waste
B2 Maintenance	Painted surfaces are maintained (i.e. repainted periodically), but no other maintenance aspects are included
B4 Replacement	A1-A5 effects of replacement materials, and C1, C2, C4 effects of replaced materials
C1 De-construction demolition	Demolition equipment energy use
C2 Transport	Transportation of materials from site to landfill
C4 Disposal	Disposal facility equipment energy use and landfill site effects
D Benefits and loads beyond the system boundary	Carbon sequestration and metals recycling

Table 3: Athena Impact Estimator system boundary included in LCA pilots (Adapted from the report of LCA results from the Athena Impact Estimator for Buildings tool).

LCA also relies on available EPDs for information from the product life cycle stage (A1-A3) with some in-house data for use and replacement stages (B1-B5), and end of life stage (C1-C4). One Click LCA uses an internal protocolto adapt their data to the regions where there are significant data gaps, which still includes Canada.

1.3.6 Pilot WBLCA calculation process and analysis

Throughout the pilots, we developed a standardized processes to generate the quantities of materials, developing BoM and conducting the WBLCAs. An overview of the general process that we followed to calculate all the assessments using Athena IE, with some variation depending on the data source and specifics of each building, is outlined here:

1. *Data extraction and processing*. The building's material quantities were extracted from the project drawings, 3D models, or cost estimates. In the case of project drawings, the research team used Bluebeam Revu software to calculate the material quantity takeoffs. The material quantities were then classified and organized in Excel.
2. *Material quantities calculations*. The quantities were organized into categories, with any necessary calculations to convert dimensions into the appropriate unit (e.g. square meters into cubic meters) and tallied by building elements.
3. *Material selection and mapping*. The building-specific materials were mapped to the selection of materials available in the LCA tool's database. If a specific material was not included in the database, the research team, with input from Athena, matched it with the most similar equivalent.

Athena IE also required the incorporation of two factors: the Construction Waste Factor, intended to account for on-site construction waste, and Unit of Measure (UoM) Multiplication Factor, which converts the imported material quantity to the units in the Athena databse. The Construction Waste Factor is a set percentage calculated by Athena IE and added to individual material quantities, then rolled into the BoM. It is added automatically in the Assembly-method inputs, and so the research team chose to incorporate it into the BoM method inputs, for consistency and comparability. The UoM Multiplication factor is only applied in the BoM method. The research team accounted for most of the unit conversion when calculating quantities but some materials in the database had set dimensions that required the research team to make additional adjustments to accommodate.

4. *Data input into LCA*. A new simplified Excel data table was created to match the Athena IE inputs requirements, including the columns' namings and appropriate units of material quantities. The Excel file is imported and the LCA tool automatically maps materials, if the material categories and names match those in its database. If the tool is unable to match, the user can do it manually and then the assessment is performed. In OneClick LCA, similar to Athena IE, a simplified Excel data table is used to prepare materials for input. OneClick LCA provides a template with a table that specifies the assembly group, material name, and quantity in acceptable units. In EC3, no file import is possible. Instead, all material selections and quantity imports are done manually in the tool. EC3 allows the user to format inputs according to Uniformat, MasterFormat, or a custom format.
5. *Result output and analysis*. The results from the LCA tool were exported to an Excel spreadsheet to be analyzed.
6. *Assessment results break-down by building elements and life cycle stages*. These results breakdowns were used to examine which building element or life cycle srage were the primary contributors of embodied carbon emissions. The results were analyzed by the research team, to explore the variations depending on data sources and tools.

While following these steps, the research team tracked all of the gaps of information encountered and other challenges, as well as assumptions, workarounds and solutions. The team also tracked the time invested in each of these activities for each of the pilots to identify the most time-intensive activities. This process-based analysis provides insights into the types of information, expertise and work required of project teams and consultants when conducting WBLCAs, which must be considered when developing guidelines and policies around the use of WBLCAs in development projects. The results of this analysis are described in greater detail in Section 3.

SECTION 2.0: LCA ASSESSMENTS

2.1 UBC FIRST NATIONS LONGHOUSE

The First Nations Longhouse, located in the northwest corner of the UBC Vancouver campus, is a single-storey, 2,000 m^2 timber building, shaped like a typical Musqueam-style longhouse. The Longhouse is part of the First Nations House of Learning, and houses programs for indigenous faculty and students, as well as serving as a community centre for First Nations, Metis and Inuit faculty students and staff. Within the building are offices, seminar rooms, a resource centre, a library and a great hall, which showcases traditional wood building techniques and decoration. The design of the building combines traditional regional wood construction styles with contemporary architectural forms. The primary structural framing, as well as interior finishes and exterior cladding, consists of regionally-harvested western red cedar. The structure is heavy timber on a concrete foundation and light wood-framed interior and exterior walls, with ship-lap plank exterior cladding and a copper roof (UBC, 2013).

The Longhouse was completed in 1992, and so the amount of project information available to the research team was limited. The main data source for the WBLCA was the Issued-for-Tender (IFT) architectural and structural drawings. We did quantity take-offs from the IFT drawings of the main building elements including foundation, structure and envelope to create a BoM. To estimate the Longhouse's embodied carbon emissions, we conducted a WBLCA based on the BoM using the Athena Impact Estimator for Buildings tool (Assessment 1).

The research team also attempted to run a WBLCA by recreating the building's components and characteristics using the construction assemblies available on the Athena IE, according to the assembly-based methodology detailed in Section 1.3. The data used for this assessment, such as dimensions, assembly geometry and materials, were based on the building's IFT drawings and the quantity takeoffs used on Assessment 1. However, the project documents provided more details than could be input into the tool, given that the Athena IE Assembly- method is intended for preliminary design only, not for fully designed and constructed buildings. Therefore, only two walls were assessed to quantify the difference in material quantities from these two methods. The details of this comparison can be found in the analysis and discussion in Section 3

Photo of First Nations Longhouse, credit Don Erhardt

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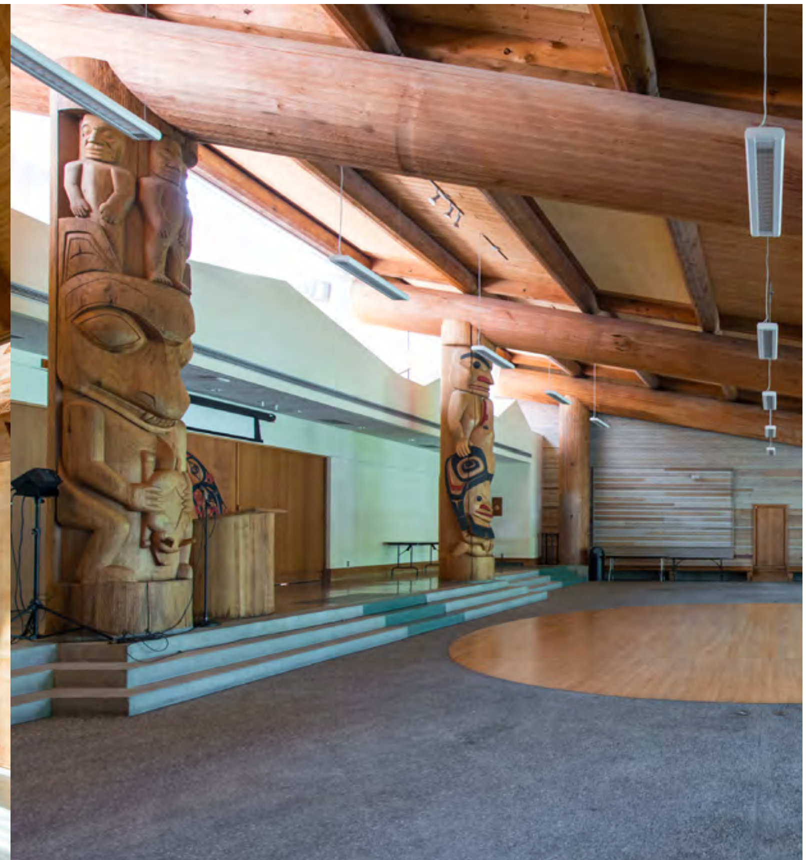
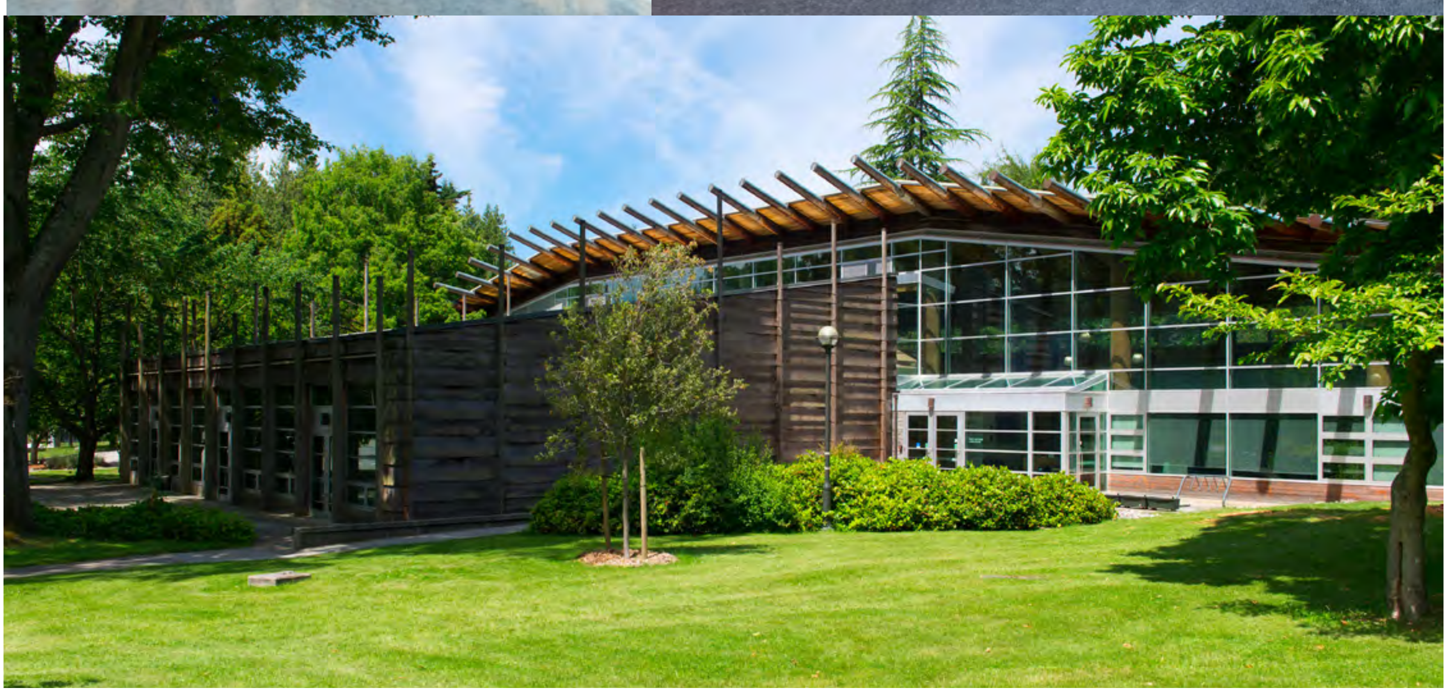




BUILDING: First Nations Longhouse

GROSS FLOOR AREA

2,226 m^2

LCA TOOL

Athena Impact Estimator for Buildings (Version 5.4.0101)

DATA SOURCE

Quantity take-offs from IFT drawings: (Post Tender Addendum#1; February 28, 1992)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction

Roof coverings and openings

Exterior walls and openings

SYSTEM BOUNDARY

Product (A1–A3)

Construction (A4–A5)

Use (B2, B4)

End of Life (C1-C4)

Benefits and loads beyond building life (D)

BUILDING LIFETIME

100 years

FINAL DRAFT

2.1.1 Assessment 1 – WBLCA using BoM from IFT Drawings

Assessment 1 consists of a WBLCA on the First Nations Longhouse based on BoM and using the Athena IE. The BoM was developed by the research team using material quantities derived through quantity takeoffs of the project's IFT architectural and structural drawings. In this case, quantities were estimated from scanned hand drawings, which required additional interpretation from the research team. The WBLCA was calculated based on the methodology outlined in Section 1.3 and included the mass timber structure, concrete foundation and exterior walls.

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-23.6	12%
Floors	-1.3	1%
Foundations	-58.4	30%
Roofs	-26.4	14%
Walls	-82.7	43%
Total	-192.4	100%

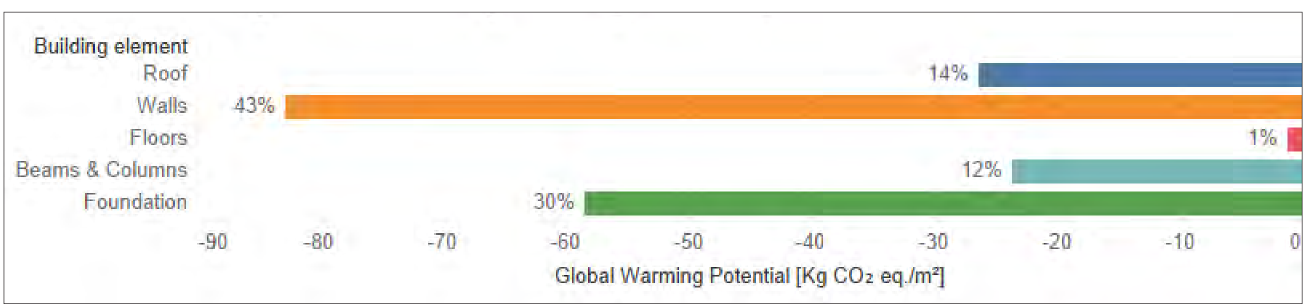


Figure 4 and Table 4: Assessment 1 WBLCA results, breakdown by building element.

FINAL DRAFT

Assessment 1 - Results

Assessment 1 estimates that the Longhouse has a total Global Warming Potential impact of 428,282 Kg of CO2 eq., or 192.4 Kg of CO2 eq. per m^2. The exterior structural walls contribute almost half of the building's embodied carbon (43%), followed by the foundation (30%). The walls are composed of red cedar shiplaps or planks with wooden detail strips, plywood sheathing, moisture/vapour/air barrier, batt insulation, wood studs and framing, and gypsum wallboard or interior cedar finish.

Almost half of the Longhouse's GWP impact is generated in the product life cycle stage (49%), followed by the replacement stage (38%). These two stages are the most production intensive for materials. It is also worth noting that, since the primary material for the superstructure is heavy timber, the carbon sequestration and the benefits beyond the building lifecycle are quite high (79%), with the potential of offsetting most of the building's total impacts.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-94.2	49%
Construction process (A4-A5)	-12.3	6%
Replacement (B2 & B4)	-73.8	38%
End of Life (C1-C4)	-12.1	6%
Total Impacts (A-C)	-192.4	100%
Benefits beyond building life (D)	148.4	77%

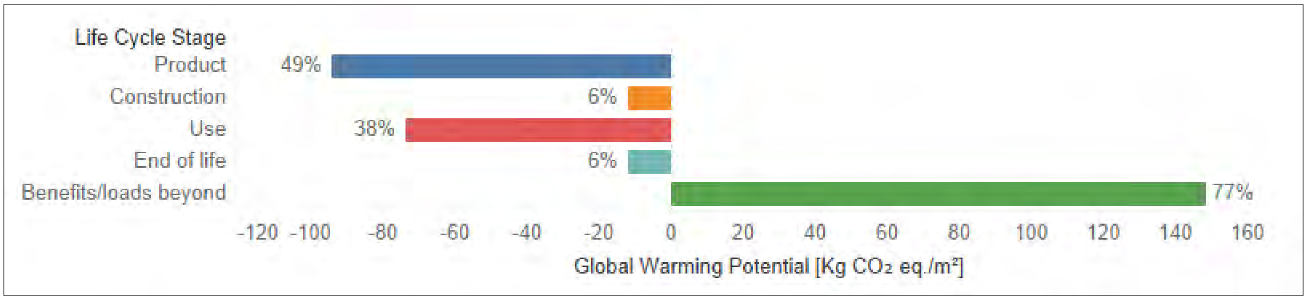


Figure 5 and Table 5: Assessment 1 WBLCA results, breakdown by life cycle stage.

2.2 UBC BIOENERGY RESEARCH AND DEMONSTRATION FACILITY (BRDF)

The Bioenergy Research and Demonstration Facility (BRDF), completed in 2012 and located on the UBC Vancouver campus, is an innovative energy generation facility that processes wood waste as biomass to generate thermal energy for the academic district energy system. It also supports academic research on biomass energy. The 1,971 m² building that houses the plant is a simple rectangular industrial-style shed. A clear span, high height section houses the energy generation system and a mezzanine area include offices, labs and a public viewing space.

The building was the first mass timber industry facility in Canada. The exposed mass timber structure is composed of cross-laminated timber (CLT) panels for the walls, floors and roof decking, and glued-laminated timber (GLT) columns and beams attached through steel connectors, supported on a slab-on-grade concrete foundation. The exterior cladding is glass and corrugated metal (UBC, 2013).

The two main data sources available for a WBLCA of the BRDF were the Issued-for-Construction (IFC) architectural and structural drawings, and a preliminary design-phase cost estimate, which compared the construction cost of two structural options: CLT panels and conventional steel and concrete. The research team used the material quantity data from the cost estimate to develop the BoM and conduct a WBLCA on this building using the BoM-approach in Athena IE (Assessment 2). This allowed us to assess the BRDF's embodied carbon based on the level of data that project teams have available in the conceptual design stage and explore the potential and accuracy of a benchmark-level WBLCA based on this data.

Photo of Bioenergy Research and Demonstration Facility, credit Don Erhardt

FINAL DRAFT

BUILDING: BRDF

GROSS FLOOR AREA

1,950 m²

LCA TOOL

Athena Impact Estimator for Buildings (Version 5.4.0101)

DATA SOURCE

Quantity take-offs from preliminary cost estimate (Preliminary Cost Estimate – Draft for review; August 12, 2009)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction and coverings

Exterior walls and openings

Interior load-bearing walls

SYSTEM BOUNDARY

Product (A1–A3)

Construction (A4–A5)

Use (B2, B4)

End of Life (C1-C4)

Benefits and loads beyond building life (D)

BUILDING LIFETIME

100 years

FINAL DRAFT

2.2.1 Assessment 2 – WBLCA using BoM from Preliminary Cost Estimate

Assessment 2 consists of a WBLCA on the BRDF using a BoM and calculated on the Athena IE tool according to the methodology outlined in Section 1.3, including the structure, foundation and envelope. The BoM was developed based on the material quantities in a preliminary design-phase cost estimate, using the mass timber structural material option that was ultimately chosen for the BRDF.

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-44.6	11%
Floors	-2.9	1%
Foundations	-227.2	55%
Roofs	-41.8	10%
Walls	-94.4	23%
Total	-410.9	100%

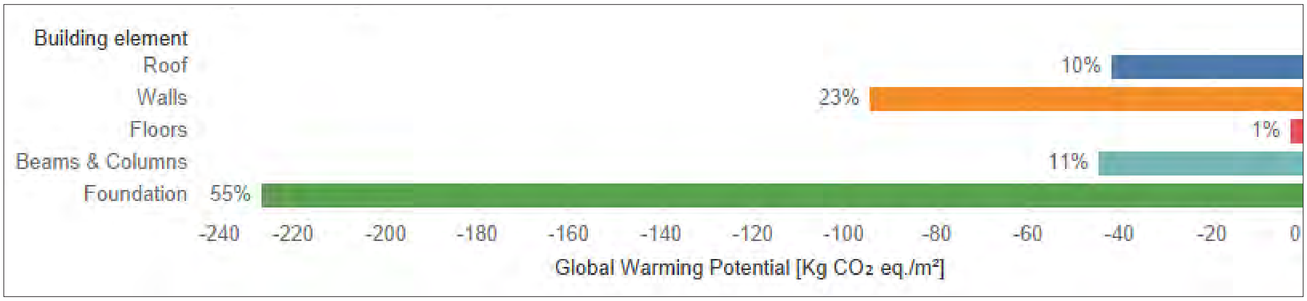


Figure 6 and Table 6: Assessment 2 WBLCA results, breakdown by building element.

FINAL DRAFT

Assessment 2 - Results

Assessment 2 estimates that the BRDF has a total Global Warming Potential impact of 801,666 Kg of CO2 eq., or 410.9 Kg of CO2 eq. per m^2. The concrete foundation has the highest impact of the building elements, contributing to more than half of the building's embodied carbon (55%). Although the most significant volume of material in the BRDF is mass timber, the total impacts from the GLT beams and columns and CLT walls were only one-third (33%) of the total GWP.

The majority of the GWP impact is generated in the product lifecycle stage (72%). This might in part be because of the prefabrication of the mass timber components, which are the primary building elements. The potential benefits beyond the life of the building could offset the GWP impacts by up to 35%, mainly from carbon sequestration in the mass timber, but also from metals recycling.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-297.9	72%
Construction process (A4-A5)	-28.4	7%
Replacement (B2 & B4)	-63.3	15%
End of Life (C1-C4)	-21.3	5%
Total Impacts (A-C)	**-410.9**	**100%**
Benefits beyond building life (D)	145.5	35%

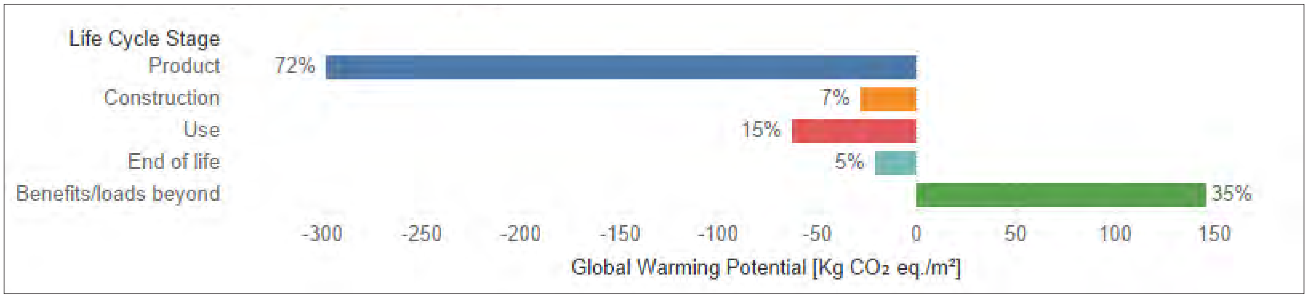


Figure 7 and Table 7: Assessment 2 WBLCA results, breakdown by life cycle stage.

FINAL DRAFT

2.3 UBC CAMPUS ENERGY CENTRE (CEC)

Located in the heart of the UBC Vancouver campus, the Campus Energy Centre (CEC) is UBC's new state-of-the-art hot water boiler facility and the primary energy source for the academic district energy system which serves over 130 buildings. Completed in 2015, it is helping UBC meet operational GHG emission reductions goals: the CEC and district energy systems reduce UBC's annual carbon dioxide footprint by 22% from 2007 baseline levels (UBC Energy & Water Services, 2020). The plant is designed to accommodate future expansions to handle increases in demand as the campus grows, and advancements in technology, such as electrical and thermal energy cogeneration, or novel thermal energy production still in development. The CEC, like the BRDF, supports education and learning through tours, interactive signage and displays.

Similar to the BRDF, the LEED-Gold-certified CEC is a large shed-like industrial building. The interior space is composed of a high-head area housing the boilers, as well as smaller offices, mechanical rooms and workspaces. Large windows on the north and west sides, provide daylighting as well as transparency and visibility for passersby. The exposed structure is a hybrid of concrete, steel, and locally sourced CLT panels, GLT columns and GLT beams, supported on a concrete slab on grade foundation. The exterior walls are a mix of insulated CLT panels, concrete and concrete masonry, with a block veneer or perforated zinc cladding, and significant expanses of glazing. The floor construction within the office areas are composite steel decking/concrete, supported on steel beams. The roof construction is primarily CLT panels on GLT beams, with composite concrete/steel decking and steel beams in some areas, supporting a rigid isolation and membrane roof.

The research team conducted seven assessments on the CEC, made possible due to the availability of a variety of project data, obtained both from the owner, UBC, and the architect, Dialog. The assessments include five data sources from different stages of design development for the CEC, as well as three different LCA software tools.

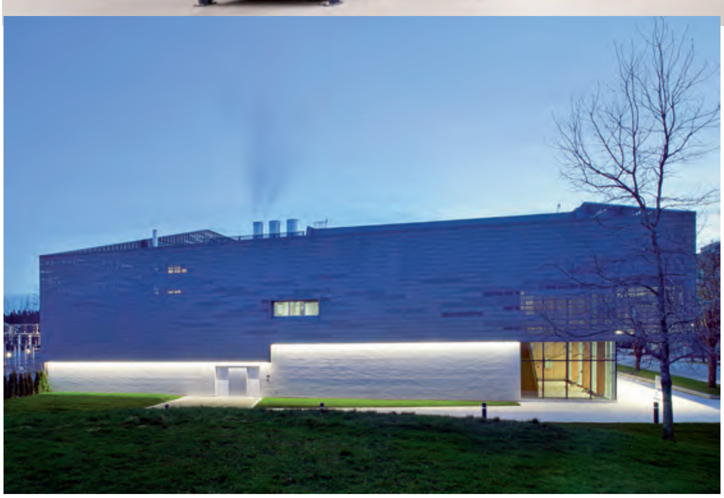
The five CEC WBLCA using Athena IE were conducted:

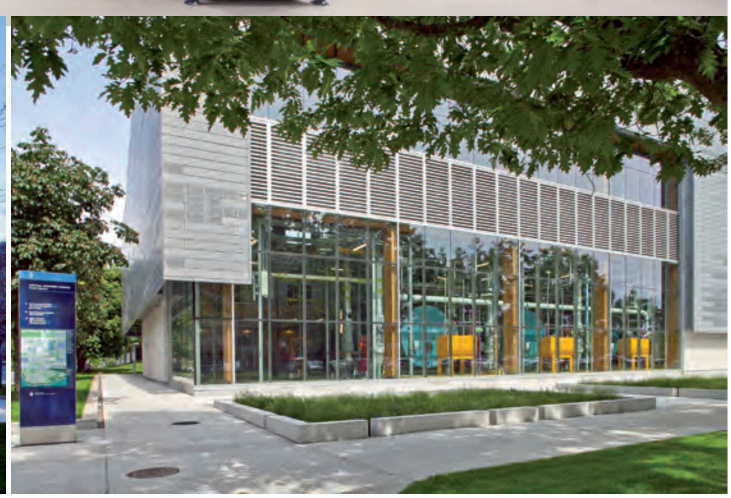
- based on construction assemblies drawn from a partial BIM model developed in the building's early design development phase using Autodesk Revit software (Assessment 3);
- from BoM exported from the same partial BIM model (Assessment 4);
- from BoM developed from materials quantities in cost estimates at two stages of drawing development (Assessments 5 and 6); and
- from BoM based on quantity takeoffs from issued-for-construction (IFC) and record drawings (Assessment 7).

We also conducted two additional WBLCA, based on BoM from IFC and Record drawings, and using Once Click LCA and the Embodied Carbon in Construction Calculator (Assessments 8 and 9).

These assessments and results are detailed in the following sub-sections. They are organized from least to most detailed, following the natural progression of a typical building design and construction project.

Photo of Campus Energy Centre, credit Ema Peter, courtesy of Dialog





BUILDING: CEC

GROSS FLOOR AREA

1,911 m²

LCA TOOL

Athena Impact Estimator for Buildings (Version 5.4.0103)

DATA SOURCE

BIM model (Issued for 80% Architectural Model; October 24, 2013 / Issued for Permit Structural Model; November 8, 2013)

DATA INPUT METHOD

Construction assemblies

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction and coverings

Exterior walls and openings

1 interior CLT load-bearing wall

SYSTEM BOUNDARY

Product (A1–A3)

Construction (A4–A5)

Use (B2, B4)

End of Life (C1-C4)

Benefits and loads beyond building life (D)

BUILDING LIFETIME

100 years

FINAL DRAFT

2.3.1 Assessment 3 – WBLCA using Assemblies from BIM model

Assessment 3 consists of an LCA, using the Assembly input method from the Athena IE tool, of the CEC's primary building elements, according to the methodology detailed in Section 1.3. The building elements include foundation (incl. rebar), floor construction, GLT beams and columns, steel beams, columns and trusses, roof construction and coverings, and exterior wall construction and cladding. Non-structural interior partition walls were excluded. The assembly-related data, such as dimensions and assembly geometry and materials, were compiled based on the assemblies modelled in architectural and structural 3D BIM model, created at about 80% design development.

The research team mapped the assemblies into the Athena IE tool, making substitutions for materials that do not exist in the tool database. CEC unique assemblies, such as custom structural members or products like the rolling door, required some workarounds including reasonable approximation of a close material and geometry, or addition of material quantities directly in an extra materials category.

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-32.6	7%
Floors	-11.5	2%
Foundations	-97.9	21%
Roofs	-63.8	14%
Walls	-256.9	56%
Total	-462.7	100%

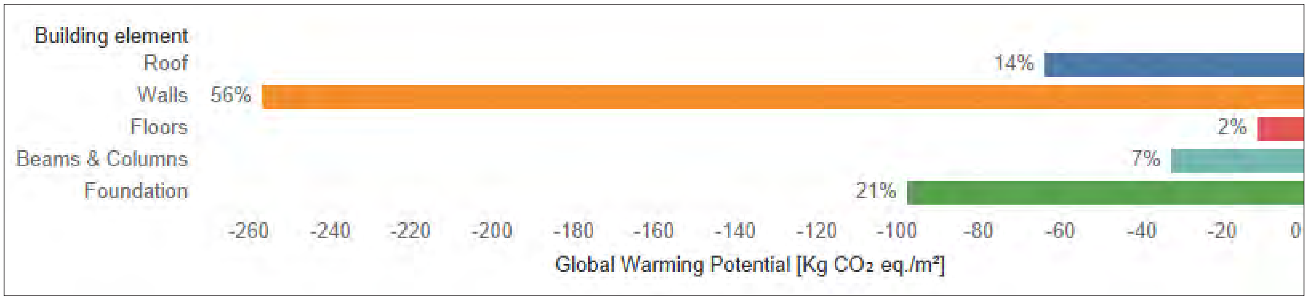


Figure 8 and Table 8: Assessment 3 WBLCA results, breakdown by building element.

FINAL DRAFT

Assessment 3 – Results

Assessment 3 estimates that the CEC has a total Global Warming Potential impact of 884,220 Kg of CO2 eq., or 462.7 Kg of CO2 eq. per m². The exterior walls contribute the most to the GWP impacts, accounting for 56% of the total impact. The second biggest contributor is the concrete slab-on-grade foundation (21%), followed by the building's roof construction and coverings. In the assembly-based approach, the structural elements, such as CLT panels, are incorporated into floors, walls, and roof construction, according to the assemblies in Athena IE, although beam and columns are kept separate. When assigning assemblies, Athena IE automatically estimates the columns and beams dimensions based on fixed span and bay sizes, includes standard details such as finishes, connections, and fasteners, which impact the final results.

Similar to the Longhouse and BRDF, the product life cycle stage of the CEC is the most carbon-intensive stage, with 64% of the impacts. The prefabrication of the mass timber structure and the minimal finishing requiring installation at the construction site are probable causes. The benefits and loads beyond the system boundary have the potential to offset up to 39% of the building's total impacts, again at least partially due to the significant quantity of mass timber and its potential carbon sequestration assumed in the Athena IE tool, as well as recycling potential of the steel and other metals.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-295.0	64%
Construction process (A4-A5)	-33.5	7%
Replacement (B2 & B4)	-112.8	24%
End of Life (C1-C4)	-21.4	5%
Total Impacts (A-C)	-462.7	100%
Benefits beyond building life (D)	179.2	39%

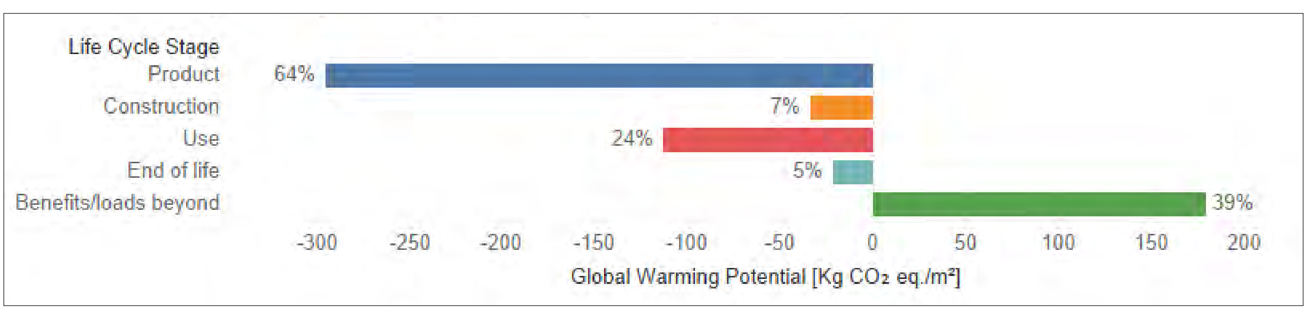


Figure 9 and Table 9: Assessment 3 WBLCA results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA

1,911 m²

LCA TOOL

Athena Impact Estimator for Buildings (Version 5.4.0103)

DATA SOURCE

BIM model (Issued for 80% Architectural Model; October 24, 2013 / Issued for Permit Structural Model; November 8, 2013)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction and coverings

Exterior walls and openings

Stair construction

Interior load-bearing walls

SYSTEM BOUNDARY

Product (A1–A3)

Construction (A4–A5)

Use (B2, B4)

End of Life (C1-C4)

Benefits and loads beyond building life (D)

BUILDING LIFETIME

100 years

FINAL DRAFT

2.3.2 Assessment 4 – WBLCA using BoM from BIM model

Assessment 4 consists of a WBLCA of CEC using a BoM from the same partial architectural and structural BIM models used in Assessment 3 (created at about 80% design development). The BoM was developed using the Revit Material Takeoff Schedule feature, according to the methodology detailed in Section 1.3. Since the model was built using Autodesk Revit software, the material quantities and properties were able to be exported directly from the model to the Athena IE tool.

The object of assessment was similar to the Assembly-based Assessment 3 and included foundation, floor construction, roof construction and coverings, exterior wall construction and cladding, stair construction and interior structural partitions. In the BoM input method, beams and columns that support the floor are accounted for in the floor construction and those that support the roof are included in the roof construction. Given that the BIM model was only partially developed for design-decision making purposes rather than material quantification, certain detailed components were not included in the model and therefore not included in the LCA. Most notably the steel reinforcement for concrete elements.

The BoM was then mapped into the Athena IE tool selecting the materials from the tool's database. The mapped material list was relatively close, but some materials had to be replaced with similar materials from the same category but not with the exact characteristics (e.g. zinc panels were entered as metal wall cladding).

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-22.6	6%
Floors	-32.5	8%
Foundations	-51.3	13%
Roofs	-82.1	20%
Walls	-213.0	53%
Total	-401.5	100%

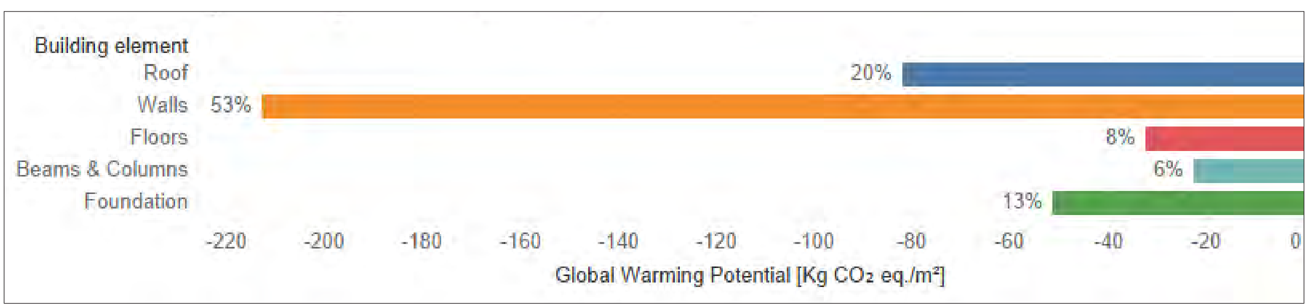


Figure 10 and Table 10: Assessment 4 WBLCA results, breakdown by building element.

FINAL DRAFT

Assessment 4 – Results

Assessment 4 estimates that the CEC has a total Global Warming Potential impact of 767,267 Kg of CO2 eq., or 401.5 Kg of CO2 eq. per m². The largest contributor to GWP impacts are the exterior walls (53%), followed by the roof construction (20%) and the foundation (13%). Compared to Assessment 3, the results for Assessment 4 are lower overall, in part due to the variations in the level of detail included in the data sources. As mentioned before, the Assembly method automatically estimates and includes standard details of assemblies, while the BoM based assessment only included elements that were modelled in the BIM model, creating variations in the object of assessment, and thus differences in the WBCLA results.

The greatest GWP impacts are from the product stage (59%) and the use stage (32%), which is consistent with Assessment 3 although varying in the specific percentage. The benefits beyond the life of the building are higher in the BoM based assessment than in the Assembly method, accounting for up to 54% of the building's total impacts and therefore almost entirely offsetting the potential GWP impacts from the product stage.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-238.2	59%
Construction process (A4-A5)	-21.5	5%
Replacement (B2 & B4)	-126.3	32%
End of Life (C1-C4)	-15.5	4%
Total Impacts (A-C)	**-401.5**	**100%**
Benefits beyond building life (D)	215.2	54%

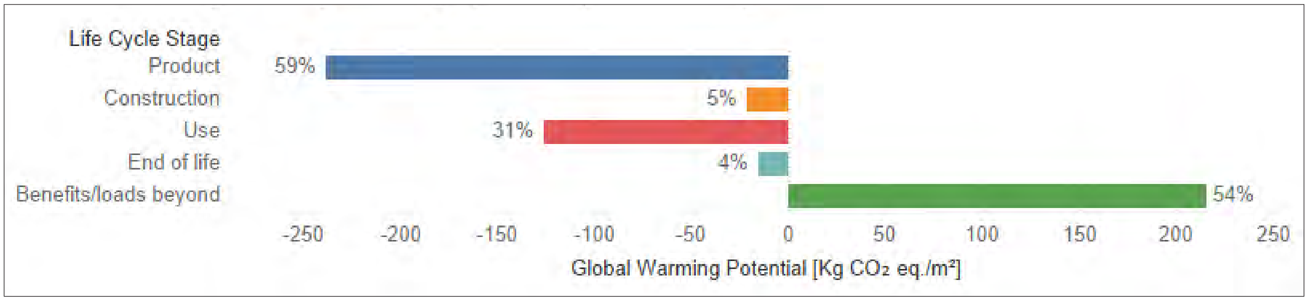


Figure 11 and Table 11: Assessment 4 WBLCA results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA

1,911 m^2

LCA TOOL

Athena Impact Estimator for Buildings (Version 5.4.0101)

DATA SOURCE

Material quantities from preliminary cost estimate - 50% design development drawings (50% Drawings Estimate; September 6, 2013)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction and coverings

Exterior walls and openings

Interior load-bearing walls

SYSTEM BOUNDARY

Product (A1–A3)

Construction (A4–A5)

Use (B2, B4)

End of Life (C1-C4)

Benefits and loads beyond building life (D)

BUILDING LIFETIME

100 years

FINAL DRAFT

2.3.3 Assessment 5 – WBLCA using BoM from 50% Cost Estimate

Assessment 5 consists of a WBLCA on the CEC using a BoM from a design development-phase cost estimate, calculated in Athena IE and according to the methodology detailed in Section 1.3. The material quantities for the BoM were taken from a professional cost estimate prepared from 50% design development drawings.

According to the cost consultant, quantities of all major elements were assessed or measured, where possible, based on the project drawings and specifications in the development permit phase. For building components and systems where specifications and design details were not available, material quantities were established by the cost consultant based on discussions with the design team.

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-17.6	5%
Floors	-14.0	4%
Foundations	-85.3	27%
Roofs	-60.2	19%
Walls	-144.4	45%
Total	-321.5	100%

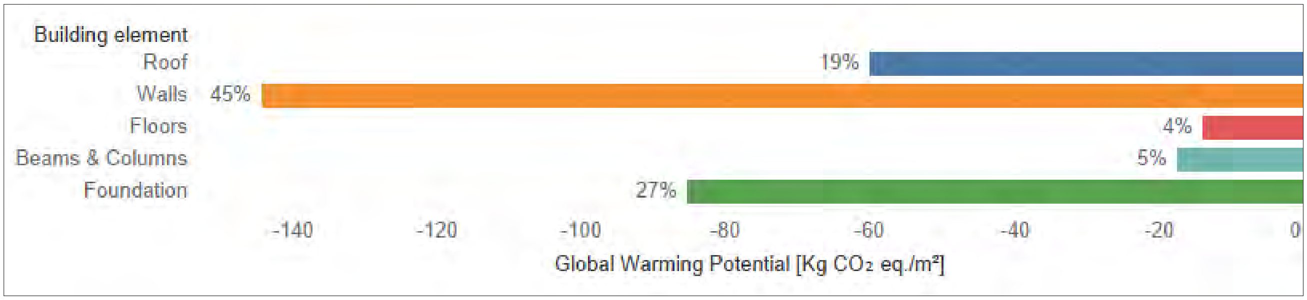


Figure 12 and Table 12: Assessment 5 WBLCA results, breakdown by building element.

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Assessment 5 – Results

Assessment 5 estimates that the CEC has a total Global Warming Potential impact of 614,387 Kg of CO2 eq., or 321.5 Kg of CO2 eq. per m². The GWP impacts calculated using the BoM data from this design-phase cost estimate are lower than the assessments based on the partial BIM model (Assessments 3 and 4). The overall material quantities were lower in the 50%-design-cost-estimate BoM than in the partial BIM model. This is possibly because more details of the design were included in the BIM models as they were developed roughly two months later than the 50% design development drawings used in the cost estimate (November versus September 2013).

The exterior walls of the CEC account for just under half of the total impacts (45%), followed by the concrete foundation (27%) and the roof construction (19%). The product life cycle stage also accounts for the vast majority of impacts (68%), followed by the use stage (21%). The benefits beyond the life of the building were significant, and at 57%, could potentially offset more than half of the building's total GWP impacts. The result breakdown is broadly consistent with the previous two CEC WBLCAs (Assessments 3 and 4), both by building elements and by lifecycle stages.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-218.0	68%
Construction process (A4-A5)	-21.5	7%
Replacement (B2 & B4)	-67.7	21%
End of Life (C1-C4)	-14.3	4%
Total Impacts (A-C)	**-321.5**	**100%**
Benefits beyond building life (D)	183.8	57%

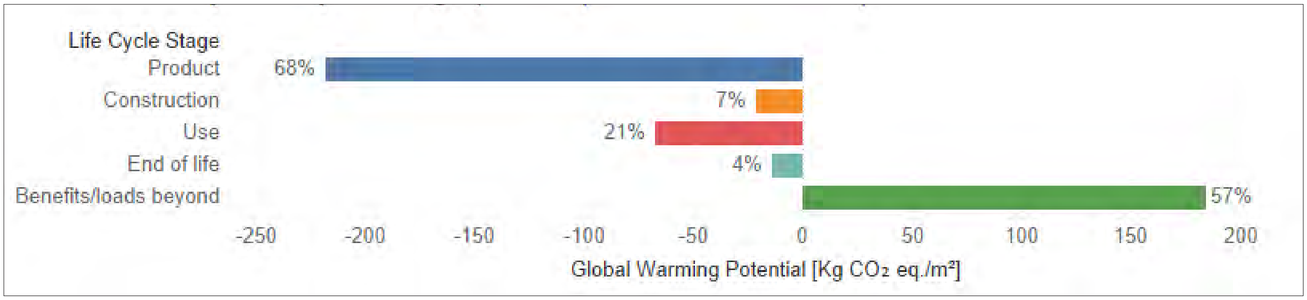

Figure 13 and Table 13: Assessment 5 WBLCA results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA

1,911 m^2

LCA TOOL

Athena Impact Estimator for Buildings (Version 5.4.0101)

DATA SOURCE

Material quantities from prelim inary cost estimate - 85% design development drawings (85% Costing Report; November 14, 2013, updated December 16, 2013)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction and coverings

Exterior walls and windows

Interior load-bearing walls

SYSTEM BOUNDARY

Product (A1–A3)

Construction A4–A5)

Use (B2, B4)

End of Life (C1-C4)

Benefits and loads beyond building life (D)

BUILDING LIFETIME

100 years

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2.3.4 Assessment 6 – WBLCA using BoM from 85% Cost Estimate

Similar to Assessment 5, Assessment 6 consists of a WBLCA on the CEC using a BoM from a design development-phase cost estimate and calculated on Athena IE according to the methodology detailed in Section 1.3. In this case, the material quantities for the BoM were taken from a professional cost estimate prepared from 85% design development drawings.

The same cost consultant was used for both the 50% and 85% cost estimates, which were developed using the same methodology. Quantities of all major elements were calculated from project drawings and specifications. Where specifications and design details are not available, quantities were established by the consultant based on discussions with the design team.

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-39.7	11%
Floors	-8.5	2%
Foundations	-72.7	21%
Roofs	-54.9	16%
Walls	-175.3	50%
Total	-351.1	100%

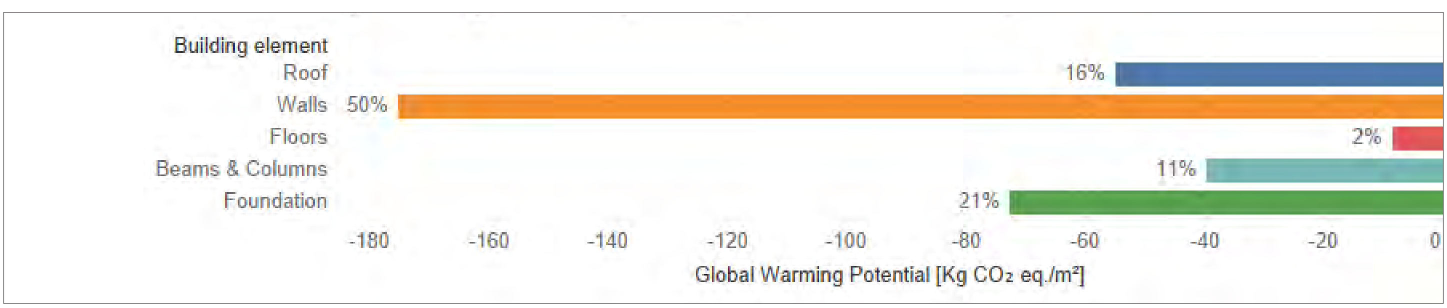

Figure 14 and Table 14: Assessment 6 WBLCA results, breakdown by building element.

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Assessment 6 –Results

Assessment 6 estimates that the CEC has a total Global Warming Potential impact equivalent to 671,952 Kg of CO2 eq., or 351.1 Kg of CO2 eq. per m². The results from this assessment are quite similar to the results from Assessment 5, both in building elements and life cycle stage, because both are based on similar design-phase cost estimates. As Assessment 6 is from a slightly later stage of design development (design development drawings were 85% complete, rather than 50%), the BoM included a greater quantity and level of detail for the building materials, and the WBLCA results are slightly higher overall.

The exterior walls remain the highest contributors to GWP impacts, accounting for half (50%) of the total impacts, followed-by the foundation and roof construction, (21% and 16% respectively). The beams and columns were still relatively small percentages (11%) but are over twice that of the previous assessment.

The product lifecycle stage remains the major contributor to GWP impacts (70%), significantly greater than the next largest, the use stage (19%). The benefits beyond the life of the building continue to be able to potentially offset about half (49%) of the total GWP impacts from the other lifecycle stages.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-246.6	70%
Construction process (A4-A5)	-22.5	6%
Replacement (B2 & B4)	-65.6	19%
End of Life (C1-C4)	-16.4	5%
Total Impacts (A-C)	**-351.1**	**100%**
Benefits beyond building life (D)	170.9	49%

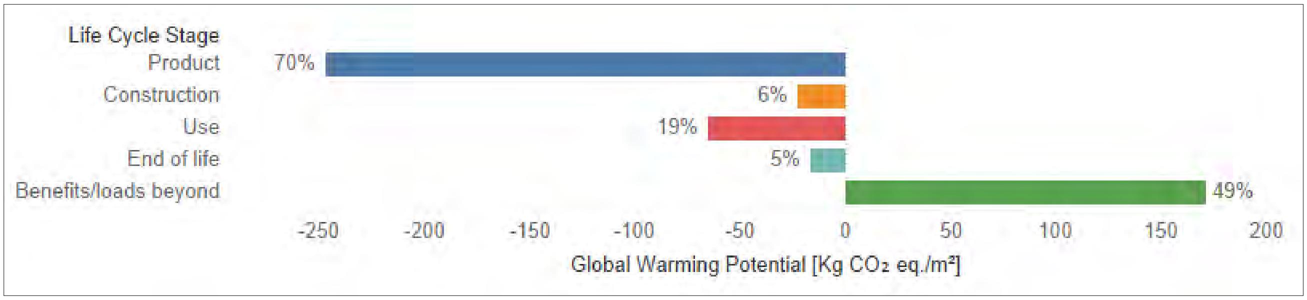

Figure 15 and Table 15: Assessment 6 WBLCA results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA

1,911 m²

LCA TOOL

Athena Impact Estimator for Buildings (Version 5.4.0101)

DATA SOURCE

Quantity take-offs from IFC and Record drawings (Architectural Record Drawings; June 29, 2016 / Issued for Construction Structural Drawings; June 6, 2014)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction and coverings

Exterior walls and openings

Stair construction

Interior load-bearing walls

SYSTEM BOUNDARY

Product (A1–A3)

Construction (A4–A5)

Use (B2, B4)

End of Life (C1-C4)

Benefits and loads beyond building life (D)

BUILDING LIFETIME

100 years

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2.3.5 Assessment 7 – WBLCA using BoM from IFC Drawings

Assessment 7 consists of a WBLCA on the CEC based on a BoM derived from IFC and Record drawings and calculated using Athena IE based on the methodology outlined in Section 1.3. The BoM was developed using material quantities from quantity take-offs on the project's architectural Record drawings and structural Issued-for-Construction drawings. Beyond these, the project specifications and some shop drawings were also consulted to find and confirm some materials. The research team used Bluebeam Revu to assist in quantifying the building's main elements from PDF scans of the drawings.

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-56.0	13%
Floors	-53.9	13%
Foundations	-62.3	15%
Roofs	-32.2	8%
Walls	-210.9	51%
Total	-415.3	100%

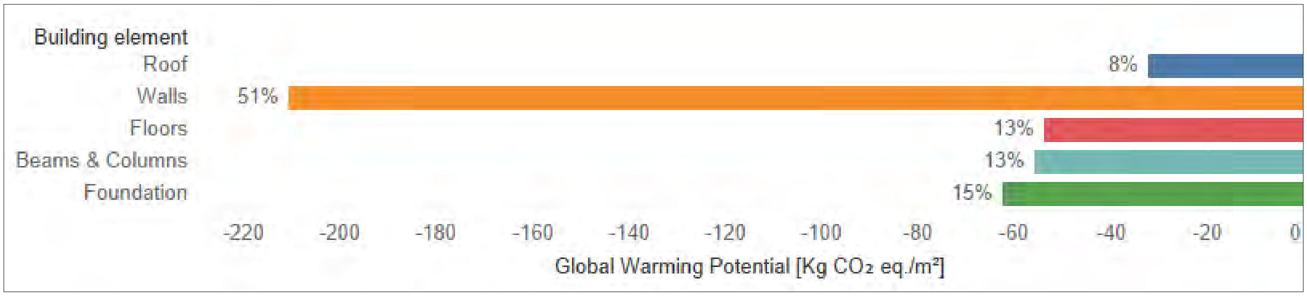

Figure 16 and Table 16: Assessment 7 WBLCA results, breakdown by building element.

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Assessment 7 – Results

Assessment 7 estimates that the CEC has a total Global Warming Potential impact of 793,638 Kg of CO2 eq., or 415.3 Kg of CO2 eq. per m². The BoM used for this WBLCA was based on drawings at effectively 100% design development. All materials of the components within the object of assessment were quantified, which led to a higher quantity of materials in the BoM and resulted in a higher GWP overall than most of the previous assessments, which were based on the BoM from the design-phase models and cost estimates.

The GWP results are similar to the results from the previous WBCLAs, in terms of the significant impact categories for the building elements and life cycle stages. The exterior walls contribute about half (51%) of the total GWP impacts, however, the foundation, floors, and beams and columns are all quite close (15%, 13% and 13%, respectively). The roofs remain the lowest contributor among the categories of building elements (8%).

The product life cycle stage remains the most significant, contributing two-thirds (66%) of the building's total GWP impacts. The use stage contributes about a quarter (24%) of the total impacts, while the construction and end of life stages remain low (6% and 4%, respectively). The benefits beyond the life of the building are estimated to offset half (50%) of the total GWP impacts, due to the carbon sequestration in the mass timber, and the potential recyclability of materials like steel.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-275.4	66%
Construction process (A4-A5)	-23.3	6%
Replacement (B2 & B4)	-98.4	24%
End of Life (C1-C4)	-18.2	4%
Total Impacts (A-C)	**-415.3**	**100%**
Benefits beyond building life (D)	208.9	50%

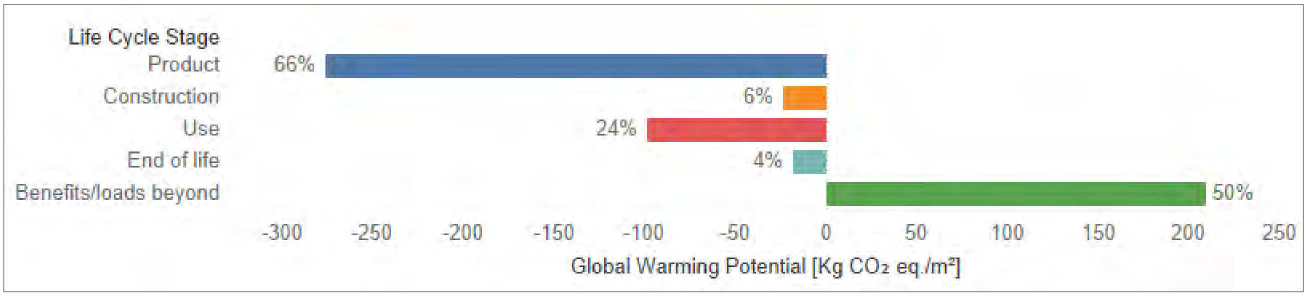

Figure 17 and Table 17: Assessment 7 WBLCA results, breakdown by life cycle stage.

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BUILDING: CEC

GROSS FLOOR AREA

1,911 m²

LCA TOOL

EC3 (Version v 22.1.1_b-1302)

DATA SOURCE

Quantity take-offs from IFC drawings (Architectural Record Drawings; June 29, 2016 / Issued for Construction Structural Drawings; June 6, 2014)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction

Stair construction

Exterior walls and openings

Interior load-bearing walls

SYSTEM BOUNDARY

Product (A1–A3)

BUILDING LIFETIME

Not applicable

2.3.6 Assessment 8 – WBLCA using EC3 tool

Assessment 8 consists of a WBLCA on the CEC, based on the same BoM from the IFC and Record drawings as Assessment 7, but conducted using a different LCA tool, the Embodied Carbon in Construction Calculator (EC3). As described in Section 1, EC3 is a new online LCA tool specifically designed to assess the embodied carbon impacts of building materials and draws on a database of industry-average and manufacturer-specific EPDs.

The BoM encompassed the same components as Assessment 7, including foundation, exterior walls and openings, roof construction (excluding coverings), floor construction, stairs, and beams and columns. This information was translated into EPDs for the major building components, based on their availability in the EC3 database. EC3 is a relatively new tool, with limitations in the available EPDs for building products and regions (most correspond to the United States, not Canada).

EC3 does not allow assessment of environmental impacts results by the life cycle stage. Because EPDs are developed by the manufacturers, most of them provide data on the product life cycle stage only. As noted above, the available EPDs did not cover all the materials in the building assemblies that are accounted for in the BoM, and so those materials were excluded from the assessment, resulting in a smaller quantity of input data.

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-73.3	20%
Floors	-75.4	21%
Foundations	-66.5	18%
Roofs	-37.4	10%
Walls	-112.2	31%
Total	-364.8	100%

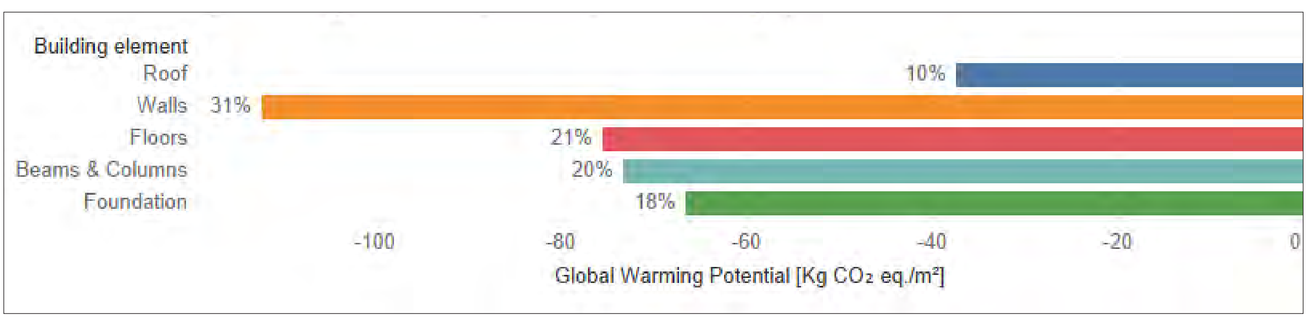

Figure 18 and Table 18: Assessment 8 WBLCA average results in EC3, breakdown by building element.

Assessment 8 – Results

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Assessment 8 estimates that the CEC has a total average Global Warming Potential impact of 697,133 Kg of CO2eq., or 364.8 Kg of CO2 eq. per m^2. The average EC3 impact is significantly lower than the GWP impacts estimated by Athena IE in Assessment 7, however, the object of assessment and system boundaries were restricted. The EC3 tool reports GWP results as a range. In order to compare with the other tools, the GWP impacts were averaged.

In terms of building elements, the division of GWP impacts across building elements is more even in the EC3 calculation than the other LCA tools, likely due to restriction to the product stage and limits of matching EPDs. The exterior walls constitute the biggest impact, consistent with the other CEC assessments, but were only 32% of the total. According to EC3, the second biggest contributor is floor construction (22%), followed by the foundation (19%), opposite that of Atehna IE.

EC3 factors in a degree of uncertainty into the LCA, to address the data gaps and variation of precisions of EPDs. EPDs of products produced at a single factory are likely to be more precise than an industry average EPD, for example, and EPDs of product with complex supply chains may have gaps of information. In EC3, the uncertainty of specific EPDs are factored into the assessment and the results reported as a range: 'conservative' result is highest estimated impact, while the 'achievable' result is the lowest (Carbon Leadership Forum, 2019). As shown in the CEC assessment, the range between the conservative and achievable can be quite large. The range in the GWP impacts of the floors, which is the greatest, is over 50%, while the range in the roof, the least, is still about 25%.

Building Element (Modules A-C)	Conservative GWP [Kg CO2 eq./m²]	Achievable GWP [Kg CO2 eq./m²]
Beams & Columns	-96.1	-50.4
Floors	-100.2	-50.7
Foundations	-88.4	-44.6
Roofs	-42.6	-32.2
Walls	-123.6	-100.9
Total	-450.9	-278.8

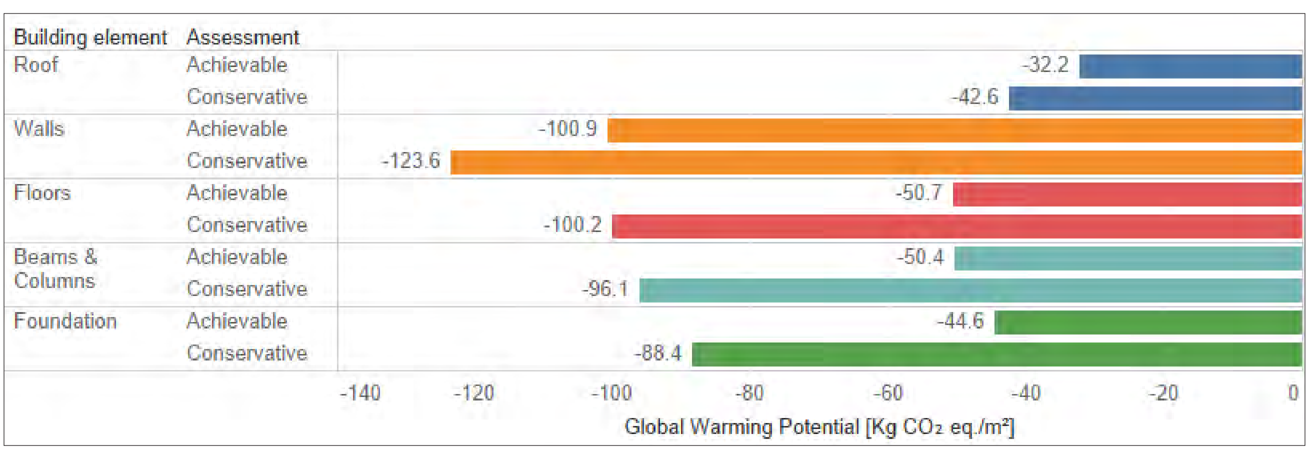

Figure 19 and Table 19: Assessment 8 WBLCA conservative and achievable results in EC3, breakdown by building element.

BUILDING: CEC

GROSS FLOOR AREA

1,911 m^2

LCA TOOL

One Click LCA (Database Version 7.6)

DATA SOURCE

Quantity take-offs from IFC drawings (Architectural Record Drawings; June 29, 2016 / Issued for Construction Structural Drawings; June 6, 2014)

DATA INPUT METHOD

Bill of Materials (BoM)

OBJECT OF ASSESSMENT

Standard foundations and slab on grade

Floor construction (incl. columns and beams)

Roof construction

Stair construction

Exterior walls and openings

Interior load-bearing walls

SYSTEM BOUNDARY

Product (A1–A3)

Construction process (A4–A5)

Use (B1-B5)

End of Life (C1-C4)

BUILDING LIFETIME

Not applicable

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2.3.7 Assessment 9 – WBLCA using One Click LCA

Assessment 9 also consists of a WBLCA on the CEC, based on the same BoM from the Record and IFC drawings as Assessments 7 and 8, but conducted using One Click LCA. As described in Section 1, One Click LCA is a web-based tool that relies on EPDs, which are used to estimate the environmental impacts from the building's products, similar to the EC3 tool. Unlike EC3, which has a database of North American EPDs for major materials, One Click LCA has an extensive pool of LCI data from across the world. It also uses an internal protocol to fill the data gaps with approximations when local and product-specific data are not available.

The BoM encompassed the same components as Assessment 7, including foundations, floor and roof construction including beams and columns, exterior walls and openings, load-bearing interior walls and stairs. Data was input to One Click LCA via an Excel sheet template, similar to Athena IE., with some materials selected manually from the databse and quanitites entered manually. Once the material sheet is imported the tool automatically maps them to the available materials within their database. For materials to successfully get mapped, they need to exactly match the material names in the library, but One Click LCA does allow users to modify the location of the materials manufacturers (if known).

Building Element (Modules A-C)	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Beams & Columns	-123.8	28%
Floors	-84.3	18%
Foundations	-73.4	17%
Roofs	-42.2	10%
Walls	-119.3	27%
Total	-443.0	100%

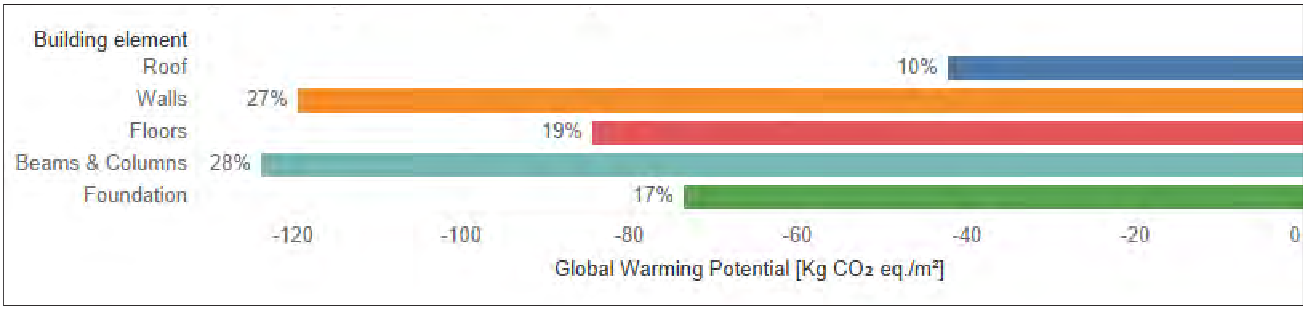

Figure 20 and Table 20: Assessment 9 WBLCA results, breakdown by building element.

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Assessment 9 – Results

Assessment 9 estimates that the CEC has a total Global Warming Potential impact of 846,573 Kg of CO2 eq., or 443 Kg of CO2 eq. per m². This impact is significantly higher than the total GWP impact estimated by the other two tools in Assessments 7 and 8. The object of assessment and systems boundaries are different from both the other tools, as well.

While the exterior walls still contribute a significant amount to GWP impacts, it is significantly lower than the other assessments. The walls' GWP impact in Assessment 9 is 119 Kg of CO2 eq. per m², which is similar to the EC3 estimate of 112 Kg of CO2 eq. per m², but substantially less than the Athena IE. However, the major difference is that in Assessment 9 the beams and columns have the highest impact above all other building elements (28%), which is different from all the other CEC assessments. The foundations, which were the second-highest contributor in the other assessments, were the fourth according to One Click LCA, although the estimated mass of the impact (73 Kg of CO2 eq. per m²), is not that much higher than other assessments. Similar to EC3, these variation likely are due to the use of available EPDs and a focus on the product lifecycle stage.

One Click LCA does allow assessment of environmental impacts by life cycle stage but does not include the benefits and impacts beyond the system boundary. The product life cycle stage still accounts for the majority of the GWP impacts (87%), however, the use stage is minimal (only 3%). This is due to a lack of data: One Click LCA only accounted for the use of a few materials in the wall category, such as plywood, siding, insulation and steel doors, due to limitations in the tool's database of EPDs.

Life Cycle Stage	Global Warming Potential [Kg CO2 eq./m²]	Impact Contribution [%]
Product (A1-A3)	-385.6	87%
Construction process (A4-A5)	-29.0	7%
Replacement (B2 & B4)	-14.3	3%
End of Life (C1-C4)	-14.1	3%
Total Impacts (A-C)	-443.0	100%
Benefits beyond building life (D)	N/A	N/A

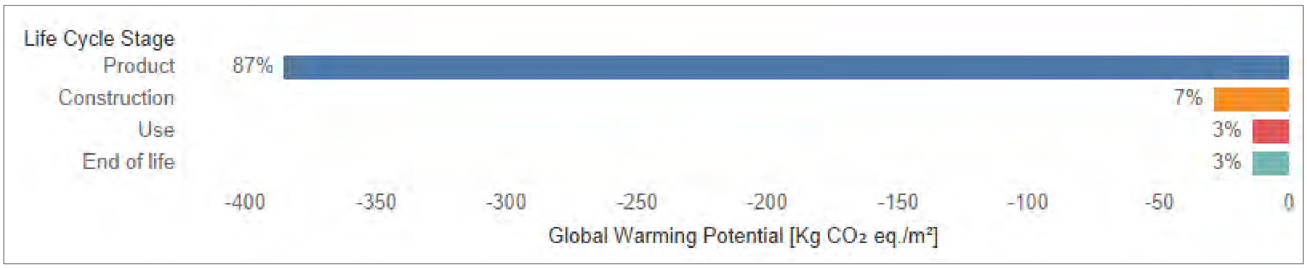

Figure 21 and Table 21: Assessment 9 WBLCA results, breakdown by life cycle stage.

SECTION 3.0: ANALYSIS AND DISCUSSION

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3.1 IMPACT OF DATA SOURCES

LCA is LCA is a complex process requiring access to extensive data, especially when applied to building projects. Buildings are complex and unique assemblies, with thousands of products and materials. At the core of a WBLCA study is the building's bill of materials (BoM), which includes the types and quantities of materials that comprise the building. Additionally, the BoM can include material waste created during product manufacturing and construction, and building material replacements and waste over the life of the building. In a comprehensive WBLCA, energy and water resource consumption over the building's life cycle are also included. However, when focusing on embodied carbon emissions or embodied GWP, the scope is limited to the buildings' materials, as described in the BoM (Athena Sustainable Materials Institute, 2020).

A BoM can be created at any stage of a project and evolve as the building design is progresses. It is developed from the project documents, most often from quantity take-offs from project drawings or 3D BIM models. A preliminary BoM from the schematic design phase has less detail and specificity than BoM created using construction documents, which provide the most accurate calculation of a building's materials. Some LCA tools, such as the Athena IE and OneClick LCA, can create an approximate BoM from data on the characteristics and geometry of the building assemblies (referred to in this report as the 'Assembly method').

The accuracy of a BoM influences the accuracy of a WBLCA. Additionally, BoM can serve as a point of comparison between building projects more effectively than WBLCA results, due to the differences between LCA tools' databases and built-in assumptions. As described in Section 1.2, Athena Sustainable Materials Institute is proposing a benchmarking methodology based on BoM, where BoM from similar typologies can be scaled towards appropriate building sizes or used statistically to create benchmarks for materials' environmental impacts, starting with GWP or embodied carbon emissions (Athena, 2020).

One of the objectives of the Embodied Carbon Pilot was to improve the use of WBLCAs in policy by studying the variations of WBLCA results based on different project data sources, and BoM calculation methods. The following analysis compares the assessments described in Section 2, specifically the differences in BoM created from different data sources, the differences in GWP results between the assessments, and the amount of work time required to create a BoM and WBLCA for each of the assessments.

3.1.1 Comparison of Assembly to BoM Methods: First Nations Longhouse

As part of the assessment of the First Nations Longhouse, the research team conducted LCAs on two of the building's walls, the Kitchen wall and Great Hall wall, using two different methods to create the BoM based on the same set of project drawings. Assessment 1 in Section 2 described the BoM method, in which a BoM was created in Excel by the research team based on material quantity take-offs calculated from the project drawings and input into the Athena IE tool. As a comparison, we also used the Assembly method to input the materials and dimensions of the wall assemblies into the Athena IE tool, based on information from the project drawings. The tool then created a BoM by aligning the project information with the assembly information within its own database. Table 22 compares the BoM for the Kitchen wall that was developed by the research team, with the one created in Atehna IE. The UoM units are set by Athena IE.

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Kitchen wall

The Longhouse Kitchen wall is a conventional wall type, and so the assembly information in the Athena IE database should be accurate. The project documents were used to construct the building, so the BoM developed from them should also be accurate. However, as illustrated in Table 22, there are distinct differences between the two BoM, including both omitted materials and variations in the quantities. Some of the detailed materials, such as nails, screws, and paint, are included by default when entering the building assemblies through the Assembly method. These materials were not quantified when doing the quantity take-offs because they were considered to be outside the object of assessment (which focused on primary components and not finishings). Connection details and fasteners are difficult to accurately quantify and have minimal impacts when compared to major components. The quantities of the major comparable materials are very similar, having the highest variation of 7% in the fibreglass insulation. Generally, the Assembly method overestimated the use of some materials, marked in the table as negative percentage values in the Comparison column, although it is also possible that the research team underestimated the same material quantities.

Material Name	UoM	Assembly	BoM	Comparison
		Quantity	Quantity	Percent Diff. (%)
Regular Gypsum Board (5/8")	m²	33.8	33.8	0.0%
Polyethylene (6 mil)	m²	32.6	31.3	-3.8%
Cedar Wood Siding	m²	135.1	135.1	0.0%
Fiberglass Insulation (R20)	m² (25mm)	174.7	162.6	-7.0%
Small Dimension Softwood Lumber (kiln-dried)	m³	0.6	0.6	-3.2%
Softwood Plywood	m² (9mm)	42.9	43.0	+0.3%
Joint Compound	Tonnes	0.1	-	-100%
Nails	Tonnes	0.1	-	-100%
Paper Tape	Tonnes	0.1	-	-100%
Screws, Nuts and Bolts	Tonnes	0.1	-	-100%
Water Based Latex Paint	Liters	72.7	-	-100%

Table 22. Comparison of material quantities of the First Nations Longhouse kitchen wall, using the Assembly and BoM input methods. Assembly method was taken as the baseline since this is the most widely used method to calculate LCAs using the Athena IE tool.

Great Hall wall

The Great Hall wall comparison showes greater variations between the BoM developed using the two methods, illustrated in Table 23. Again some of the detail materials, specifically fasteners and finishes, were not quantified through the quantity take-offs from the project drawings underthe BoM method but were included by default in Athena IE calculation through the Assembly method. All other major material quantities are accounted for in both assessments. Generally, the quantities of the major material components were higher in the Assembly method, except for the softwood lumber and plywood. Without additional information, it is difficult to determine whether the Atehna IE overestimated or if the research team underestimated the materials' quanities.

The quanitity of fibreglass insulation is significantly larger in the BoM created through the Assembly method, both in percentage and total quantity (53.7% and 301.5 m2). This is especially interesting because insulation generally has a high GWP, but is critical in reducing operational energy use (and operational carbon emissions). Accurately assessing the quantity of insulation is important for balancing the tradeoffs between operational and embodied carbon emissions. Inaccuracies in tools or human errors in quanity takeoffs can change the GWP results in ways that undermine the design decisions. Transparency is important to understand both how BoM are developed, and their impacst on the GWP impacts. These issues are explored more int eh following analysis.

Material Name	UoM	Assembly	BoM	Comparison
		Quantity	Quantity	Percent Diff. (%)
Organic Felt (#15)	m2	562.1	531.2	-5.5%
Polyethylene (6 mil)	m2	104.6	95.1	-9.1%
Cedar Wood Siding	m2	433.9	410.1	-5.5%
Fiberglass Insulation (R20)	m2 (25mm)	561.1	259.6	-53.7%
Small Dimension Softwood Lumber (kiln-dried)	m3	1.9	5.5	+194.3%
Softwood Plywood	m2 (9mm)	137.7	179.5	+30.3%
Nails	Tonnes	0.0	-	-100.0%
Screws, Nuts and Bolts	Tonnes	0.0	-	-100.0%
Water Based Latex Paint	Liters	233.4	-	-100.0%

Table 23. Comparison of material quantities of the First Nations Longhouse Great Hall wall, using the Assembly and BoM input methods. Assembly Method was taken as the baseline since this is the most widely used method to calculate LCAs using the Athena IE tool.

3.1.2 Comparison of data sources and BoM calculation methods: Campus Energy Centre

As described in Section 2, the project team performed five WBLCAs on the CEC building using the Athena IE tool. The asesseements were based on BoM from four different project data sources (partial BIM model from 80% design development, cost estimates at 50% and 85% design development, and IFC/Record drawings), and that used four different calculation methods.

The five LCAs, with their project data source and the BoM method of calculation, are listed in Table 24. In all cases, except for Assessment 3, once the BoM was generated, it was organized and mapped to the materials selection in the Athena IE database by the research team then imported into the Athena IE tool. For Assessment 3, the research team follow the Assembly method of input material and geometry information, and the BoM was created by the Atehna IE tool.

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LCA Assessment#	Project Data Source	BoM Calculation Method
Assessment 3 – Assembly method LCA	BIM model (partial)	BoM generated by Athena IE based on input of assembly materials and dimensions (sourced from BIM model)
Assessment 4 – BoM method WBLCA	BIM model (partial)	BoM exported directly from the Revit model software
Assessment 5 – BoM method WBLCA	Professional cost estimate – 50% design development	BoM created by cost consultants based on design development documents
Assessment 6 – BoM method WBLCA	Professional cost estimate – 85% design development	BoM created by cost consultants based on design development documents
Assessment 7 – BoM method WBLCA	IFC and Record drawings	BoM developed in Excel using material quantity take-offs from scanned PDFs

Table 24. Data source and calculation methods to create the BoM for each CEC WBLCA assessed using Athena IE.

The different data sources and BoM calculation methods led to variation in the types and quanities of materials included the BoM from one assessment to another. A representative list of material categories and quanities calculated for the five Atehena IE assessments is shown in Table 25.

The Assembly method, in Assessment 3, creates the list with the most variations in the material types because the Athena IE tool, by default, estimates quantity values for materials like fasteners and finishes. These were excluded from the object of assessment in other WBLCAs. The BoM in Assessment 4, which used the BIM model, relies on the specific materials included in that model, which were generally major components but not details like steel fasterners.

Mass [tonnes] / Materials	Assessment 3 (Assembly)	Assessment 4 (BIM)	Assessment 5 (50% Cost Est.)	Assessment 6 (85% Cost Est.)	Assessment 7 (Project drawings)
Wood - Mass Timber	250.1	335.9	248.5	330.3	276.7
Wood - Smaller Members	0.5	0.1	0.4	6.1	2.1
Steel - Major Structural Members	72.0	65.4	69.0	107.7	117.8
Steel - Secondary Components	2.4	11.3	-	2.2	33.6
Extra - Steel Fasteners	2.5	-	-	5.2	-
Sheet Metal - Cladding	26.4	30.3	39.5	20.2	39.9
Aluminum - Window Frames & Mullions	9.8	1.4	-	-	4.3
Glass - Curtain Wall & Punched Window Glazing	86.3	69.1	-	44.0	42.9
Concrete - Structural	1,283.4	839.4	1,144.5	1,079.2	1,023.5
Concrete - Bricks & Blocks	444.4	553.4	375.2	349.5	346.1
Insulation	19.9	4.9	26.9	17.7	8.7
Gypsum	19.2	26.1	16.5	20.9	7.9
Barriers & Membranes	34.8	22.1	23.1	-	4.2
Extra - Grout, Joint Compound, Mortar & Paper Tape	130.2	-	-	-	-
Extra - Paint	0.1	-	-	-	-

Table 25. Comparison of a representative list of materials between the BoMs of each CEC WBLCA, variations due to differences in the data source and BIM calculation method. Materials are shown in metric tonnes for comparability.

The BoM in Assessment 5, created by the cost consultant as part of the 50% design cost estiamte, includes the least amount of materials. The project documents used for this BoM were the earliest in the design development process, which again focused on major components and dod not yet include quantities for elements like window frames and glass. The BoM in Assessment 6, created created by the cost consultant as part of the 85% design cost estiamte, is more comprehensive since the design documents were further developed. Some elements, such as barriers and membranes, were dropped, however. This might be due to design changes or because they were quantified as part of a different building element in the BoM.

The BoM developed from quantity take-offs from the IFC and Record drawings for Assessment 7 should have includes all building materials except the steel fasteners and finishes. The finishes were out of scope, and the fasteners were either not shown or were not able to be accurately and efficiently calculated from project drawings, and therefore were excluded from the quantity take-offs that created the BoM.

The variation in data sources and BoM calculation methods also led to variation in material quantities in different BoMs in each assessment. Table 26 illustrates this comparison through a colour-code. Each material quantity (rows) was compared horizontally with each other and then colour coded to highlight the highest quantities. In other words, the darker the green colour, the higher the quantity of that material among the five assessments is.

The BoM in Assessment 3, developed through the Assembly method, has the highest quantities in six of the material type categories, and overall the material quantities are generally higher than the other BoMs. The 'extra' categories are the highest by default, because those mateirals are not included in the scope for the other BoM. The rest of the high mateirals categories, however, likely reflect the built in assumptions of the standard assemblies in Athena IE. The question then becomes, how close are the standard assemblies to the actual building? The CEC has a rather unique architectural and structural

Mass [tonnes] / Material Type	Assessment 3 (Assembly)	Assessment 4 (BIM)	Assessment 5 (50% Cost Est.)	Assessment 6 (85% Cost Est.)	Assessment 7 (Project drawings)
Wood - Mass Timber	250.1	335.9	248.5	330.3	276.7
Wood - Smaller Members	0.5	0.1	0.4	6.1	2.1
Steel - Major Structural Members	72.0	65.4	69.0	107.7	117.8
Steel - Secondary Components	2.4	11.3	-	2.2	33.6
Extra - Steel Fasteners	2.5	-	-	5.2	-
Sheet Metal - Cladding	26.4	30.3	39.5	20.2	39.9
Aluminum - Window Frames & Mullions	9.8	1.4	-	-	4.3
Glass - Curtain Wall & Punched Window Glazing	86.3	69.1	-	44.0	42.9
Concrete - Structural	1,283.4	839.4	1,144.5	1,079.2	1,023.5
Concrete - Bricks & Blocks	444.4	553.4	375.2	349.5	346.1
Insulation	19.9	4.9	26.9	17.7	8.7
Gypsum	19.2	26.1	16.5	20.9	7.9
Barriers & Membranes	34.8	22.1	23.1	-	4.2
Extra - Grout, Joint Compound, Mortar & Paper Tape	130.2	-	-	-	-
Extra - Paint	0.1	-	-	-	-

Table 26. Comparison of variations in materials quantities between different BoMs of CEC LCAs, due to differences in data sources and BoM calculation methods.

design, so the standards may not be that accurate. On the other hand, the Assemly method may be picking up deails not included in the scope of the other BoM, that together create a meaningful impact.

The BoM for Assessments 5 has the lowest quanities of mateirals, which makes sense, since it was based on the earliest project documents, with preliminary information on the components. Generally the materials quanities increase correlates to the design development progress, before reducing slightly between the Assessment 6 and 7 (which are based on 85% design development and construction docuemtnation). This could be more information being includeing in project documentation through the design, before being refined at the end.

In general, there are major variations in the quantities calculated for most of the materials from the different data sources and different BoM calculation methods. For example, the amount of mass timber varies as much as 87.4 tonnes across the assessments, with an average total mass timber quantity of 288.3 tonnes. The amount of concrete is also quite variable, ranging from 839.4 tonnes to 1,283.4 tonnes, a total difference of 444 tonnes.

Overall, however, the higher quantities of materials across the BoM will lead to an higher total GWP impact, although certain materials have greater embodied emissions than others. Both quanitity and type of material need to be assessed to determined influence on GWP and embodied carbon. We are interested in trying to determine at what point in the project design is there sufficient information to develop an accurate WBLCA and reflect the real impacts of materials choices, as well as which materials need to be included in the BoM. This analysis begins to explore this issues, the comparison are analysed in more detail in the following section.

3.1.3 Details comparison of data sources and BoM calculation methods: Campus Energy Centre

A more in-depth comparison of the material quantity variations across the BoM used in the different assessments can be found below: comparing the Assembly method and BoM method from the partial BIM model (Table 27); comparing the two BoM from the cost estimates (Table 28); comparing the BoM from the 85% design cost estimate and the IFC/Record drawings (Table 29).

When comparing the BoMs in these tables, it is important to analyze both the differences in percentage and the quantity of materials. There may be instances where the percentage differences are high, but the actual material quantities are low, therefore this difference will not have a significant impact on the total GWP. On the contrary, some materials have low percentage differences, but because of the high actual quantities, even slight incremental differences in the percentages could significantly increase or decrease the material quantities and the total GWP.

Assembly method and BIM model BoM comparison

In this analysis, we compare a representative selection of mateirals quantities from two different methods of estimating a BoM: Assembly method and direct export of BoM from BIM model software . These two assessments share the same data source: the partial BIM model. The percentage difference was calculated with the Assembly method as the baseline since this is the most widely used method to calculate LCAs using the Athena IE tool.

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Material Type / Mass [tonnes]	Assessment 3 (Assembly)	Assessment 4 (BIM)	Comparison Difference [%]
Wood - Mass Timber	250.1	335.9	+34%
Wood - Smaller Members	0.5	0.1	-80%
Steel - Major Structural Members	72.0	65.4	-9%
Steel - Secondary Components	2.4	11.3	+376%
Extra - Steel Fasteners	2.5	-	-100%
Sheet Metal - Cladding	26.4	30.3	+15%
Aluminum - Window Frames & Mullions	9.8	1.4	-85%
Glass - Curtain Wall & Punched Window Glazing	86.3	69.1	-20%
Concrete - Structural	1,283.4	839.4	-35%
Concrete - Bricks & Blocks	444.4	553.4	+25%
Insulation	19.9	4.9	-75%
Gypsum	19.2	26.1	+36%
Barriers & Membranes	34.8	22.1	-37%
Extra - Grout, Joint Compound, Mortar & Paper Tape	130.2	-	-100%
Extra - Paint	0.1	-	-100%

Table 27: Comparison of BoM between Assembly and BIM methods based on the partial Autodesk Revit 3D BIM model.

The materials with the lower quantities in the Assessment 4 (shown in Table 27 as negative percentages in shades of red and orange) include the aluminum in window frames and mullions, major structural steel elements, curtain wall and window glazing, structural concrete, insulation and membranes, which range between 9% - 85% difference. The wood smaller members, which include blocking and similar, have a largepercentage difference , but the total different in quantity of material for these elements is minor. Some materials were excluded in the BoM method that were included automatically in the Assembly method calculation.

The materials with the higher quanities in Assessment 4 (shown in Table 27 as positive percentages in shades of green) are the mass timber, secondary steel components, metal cladding, concrete blocks and gypsum board, generally range between 15% - 36% difference. The secondary steel components are an outlier, with more than four times the quantity calculated by the Assembly method (2.4 vs 11.3 tonnes, a 376% difference). Since the production of metals like steel has significant carbon emissions, large variations like this can significantly impact GWP results.

Although Assessments 3 and 4 share the same data source, the material quantities of each BoM vary substantially, which point to variation in the BoM calculation methods. These variations include difference in object of assessment, indicated by differents in the scope of materials included in the BoM; differences in the approach to quantifying materials, based on standard assemblies or calculated by the BIM model; and differences in categorization of materials, especially small ones, again based on the assumptions within the Atehna IE or the AutoCad Revit model.

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Design drawings cost estimate BoM comparison

In this analysis, we compare a representative selection of material quantities from BoM from two different data sources: cost estimates at 50% and 85% design development. These BoM were compiled by a professional cost consultant as part of the cost estimate based on design development documents. The the method of creating the BoM was the same for both, and the consultant used the same types of documents, but the level of details in the documents was different. This analysis therefoes compares BoM developed using the same calculation method but from two different data sources.

The percentage difference was calculated with the BoM from Assessment 5 (50% design cost estimate) as the baseline. Similar to the previous table, where the BoM quantities from Assessment 6 (85% design cost estimate) are lower, the comparison is shown as a negative percentage and highlighted in shades of orange; where it is higher, the comparison is shown as a positive percentage and highlighted in shades of green.

Material Type \ Mass [tonnes]	Assessment 5 (50% Cost Est.)	Assessment 6 (85% Cost Est.)	Comparison Difference [%]
Wood - Mass Timber	248.5	330.3	+33%
Wood - Smaller Members	0.4	6.1	+1,284%
Steel - Major Structural Members	69.0	107.7	+56%
Steel - Secondary Components	-	2.2	N/A
Extra - Steel Fasteners	-	5.2	N/A
Sheet Metal - Cladding	39.5	20.2	-49%
Aluminum - Window Frames & Mullions	-	-	N/A
Glass - Curtain Wall & Punched Window Glazing	-	44.0	N/A
Concrete - Structural	1,144.5	1,079.2	-6%
Concrete - Bricks & Blocks	375.2	349.5	-7%
Insulation	26.9	17.7	-34%
Gypsum	16.5	20.9	+26%
Barriers & Membranes	23.1	-	-100%
Extra - Grout, Joint Compound, Mortar & Paper Tape	-	-	N/A
Extra - Paint	-	-	N/A

Table 28: Comparison of material quantities from the BoM from two preliminary cost estimates calculated at 50% and 85% design development.

The BoM from these two different data sources vary as expected. As the building design was developed, more information and details were added to the drawings, which enabled a more detailed calculation of the BoM. More material categories are included in the BoM from the 85% design cost estimate, and generally the quantities are higher. The only material that was considered in the first estimate and was later removed were the barriers and membranes, which were likely either incorporated into a different category by the consultant or removed due to changes in the design.

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The elements that represent the most variation, both in terms of quantity and percentage difference, are the mass timber and structural steel elements, metal cladding, insulation, and gypsum board. The quantity for wood smaller members has the highest increase in the 85% cost estimate (1,284%), but the actual quantities are much smaller than the other structural elements. These materials are major wall components and it makes sense that design decisions in the development phase would include refinement to the exterior walls. The increases in the structural mass timber and steel elements are likely due to design changes as more accurate loading information was incorporated.

The quanitity of metal cladding in the BoM from Assessment 5 was quantified at 39.5 tonnes, which is one of the highest estimations across all five assessments, but in the BoM from Assessment 6 it is much lower, at 20.2 tonnes. This was possibly a temporary change to the design since the quantity of cladding in the BoM based on the IFC drawings (assessment 7) is almost the same as that of the BoM from the 50% design cost estimate (39.9 and 39.5 tonnes respectively).

85% Cost Estimate and IFC drawing BoM comparison

In this analysis, we compare the BoM from the 85% design cost estimate (Assessment 6) with the BoM developed by the research team based on the IFC and Record Drawings (Assessment 7). In terms of data source, the IFC and Record drawings (effectively 100% design development) contain more detail and information than the 85% design development drawings. The BoM calculation method was the same , since both BoM are based on quantity take-offs from project drawings, however they were developed by two different entities: the professional cost consultants and the research team.

The percentage differences were calculated with the BoM from Assesment 6 (85% design cost estimate) as the baseline. Again, where the BoM from Assessment 7 (IFC/Record Drawings) is lower, the comparison is shown as a negative percentage and highlighted in shades of orange; when it is higher, the comparison is shown as a positive percentage and highlighted in shades of green.

Mass [tonnes] / **Material Type**	**Assessment 6 (85% Cost Est.)**	**Assessment 7 (Project drawings)**	**Comparison** Percent Diff. (%)
Wood - Mass Timber	330.3	276.7	-16%
Wood - Smaller Members	6.1	2.1	-65%
Steel - Major Structural Members	107.7	117.8	+9%
Steel - Secondary Components	2.2	33.6	+1,427%
Extra - Steel Fasteners	5.2	-	-100%
Sheet Metal - Cladding	20.2	39.9	+97%
Aluminum - Window Frames & Mullions	-	4.3	N/A
Glass - Curtain Wall & Punched Window Glazing	44.0	42.9	-2%
Concrete - Structural	1,079.2	1,023.5	-5%
Concrete - Bricks & Blocks	349.5	346.1	-1%
Insulation	17.7	8.7	-51%
Gypsum	20.9	7.9	-62%
Barriers & Membranes	-	4.2	N/A
Extra - Grout, Joint Compound, Mortar & Paper Tape	-	-	N/A
Extra - Paint	-	-	N/A

Table 29: Comparison of material quantities from the two BoM developed from the 85% development drawings (by the professional cost consultant) and the IFC and Record Drawings (by the research team).

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The primary purpose of this comparison is to assess the differences between BoM from project drawings at 85% design development and construction (IFC is effectively 100% design development) due to changes and finalization of the building design. Secondarily, it provides an opportunity to assess the level of variation between the quantity take-offs done by two different entities, a professional quantity surveyor and the research team.

Generally, the materials quantities in the BoM from Assessment 7 are lower than the BoM Assessment 6. Which could indicated a refinement of the design and associated materials dimensions as the drawings are finalized for construction, or variancy in the material quantity takeoff process between the cost consultant and the research team. As a professional, the cost consultant has greater familiarity with the process and understanding of which details need to be included. This is supported by the includion of the steel fasteners in the BoM from the 85% design cost estimate, a level of detail that was kept out of the scope of the BoM from IFC/Record drawings.

On the other hand, the most significant variation in the camparision is for the secondary steel components, which increased from 2.2 tonnes in the BoM in Assessment 6 to 33.6 tonnes in the BoM from Assessment 7, a 1,427% increase. In this case, the IFC drawings are likely more detailed than the drawings used for the 85% design cost estimates, and included more components in this category, which would include connection between mass timber structural elements as well as smaller steel elemetns. As a tulity building, steel is a common materials in the CEC.

Another relevant increase is in the metal cladding, which almost doubles from the BoM for the 85% design cost estimate to the BoM from the IFC and Record drawings. The quantity from the IFC/Record drawings is also close to the quantity from the 50% design cost estimate in Assessment 5, which makes the 85% design cost estimate the annomoly and points to a change in design, that was later reversed, or possibly an omission or error in the documents or quantity takeoffs.

As illustrated in the the comparison between assessments, there are many potential factors than can influcen the materials categories and quanitites in cluded in BoM. These variations are carried through and influence the variations in the WBCA results. It is not always possible to understand why variances exist between different BoM–although this research highlights a few possibilities–but knowing the extent and magnitude of the variances can help to contextualize the WBLCA results. The following section explores the variations in the GWP impacts from the different assessments.

3.1.4 Comparison of GWP for different data sources: Campus Energy Centre

As illustrated in the comparison in the previous section, variations in the data sources and BoM calculations methods will influence the quanities of materials in the BoM. This will in turn influence the results of the WBLCA.

The results from each of the WBLCA of CEC using Athena IE were described in Section 2 (Assessments 3-7), and the total GWP impacts are compared in the graphs below, broken down by building element (Figure 22) and life cycle stage (Figure 23). There is a significant variation among the GWP impacts, driven by the differences in the BoMs, which are due to differences in data sources and BoM calculation methods (see Section 3.1.2). Similar to Section 2, the GWP impacts are shown as negatives values on

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the left side of the graph, while the benefits beyond the life of the building (which effectively offset the impacts) are shown as positive on the right side of the axis.

CEC GWP impacts breakdown by building element

The varying magnitudes of the GWP impacts correspond to the variations in materials quanities in the BOM. Confirming the direct connection between the BoM information and the WBLCA results. The Assembly method based LCA has the highest GWP impact of all the assessments, as well as the greatest quantities of materials. As shown in Section 3.1.2, the Assembly method also has the most detailed level of elements included in the BoM because of how the Athena IE tool calculated the BoM. However, these assumptions are based on standardized assemblies and may not directly match the actual materials in the building, so the GWP impacts may be an overestimation.

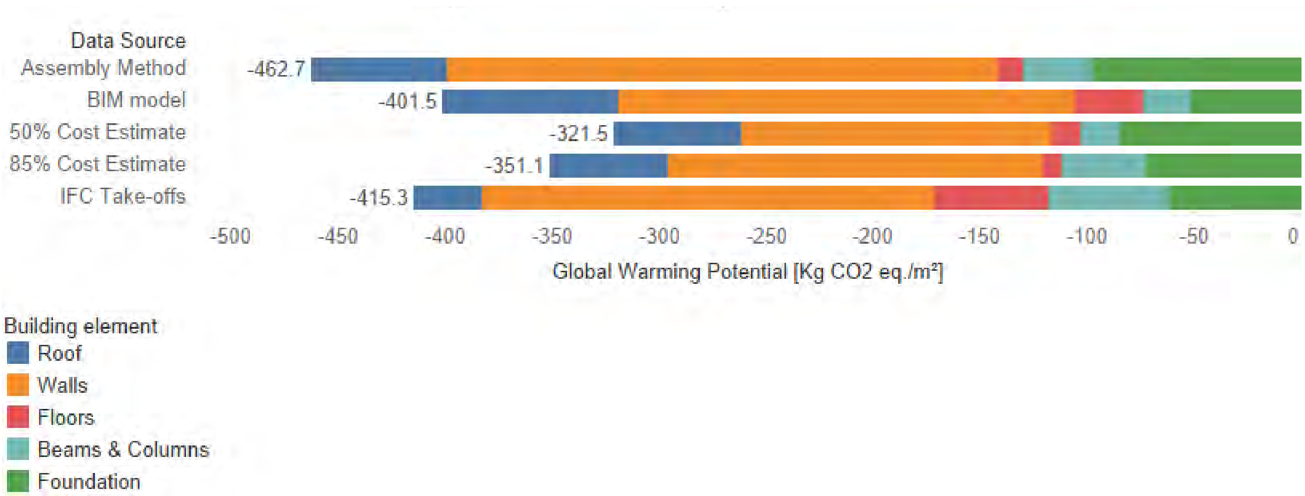

Figure 22: Comparison of GWP (embodied carbon) impacts of the CEC building estimated through WBLCA using different data sources and BoM calculation methods, and broken down by building element.

The variations through the other four assessments, particularly the three based on the progressive stages of design development (the cost estimates and and IFC takeoffs), roughly follow the progression of the building design. More accurate and detailed information is added to the drawings as the design is developed and documents prepared for construction, the material quanities in the BoM increase. However, the proportion of impacts from the different building elements do not vary proportionally with the progression: the impact of the roof decreased, while the impacts from floors and beams and columns increased, and the impacts from the foundation and walls had no trend. This may be because of changes in design decisions and associated material choices.

The higher results from the BoM from the BIM model could potentially be due to the more simplified and possibly larger geometries used in the model, as compared to the drawings. Interestingly, the total GWP impacts in the assessments based on the BIM model and IFC takeoffs are close, 401.5 and 415.2 Kg of CO2 eq/m2 respectively. This is likely a coincidence, however, because the breakdown of the GWP by building elements is very different between the two, which reflect differences in their respective BoMs.

It should also be noted that the BoMs for the BIM model and IFC based assessments were developed by the research team, while the BoMs from the two cost estimates were done by a professional cost consultant, whose approach may have been more conservative, or the research team may have consiis-tenly overestiamed certain components.

CEC GWP impacts breakdown by life cycle stage

The GWP impacts show more consistency between the five assessments when broken down by life cycle stage, Figure 23. Although there is variation in the total GWP impacts, the distribution across the building life cycle stages between the assessments is fairly consistent. This is partially influenced by the LCA too. All the assessments used the same WBLCA tool, Athena IE, which applied consistent assumptions for the impacts of different life cycle stages. Additionally, the decisions around mapping the BoM mateirals to the Athena IE database were made for one assessment and then applied to the others.

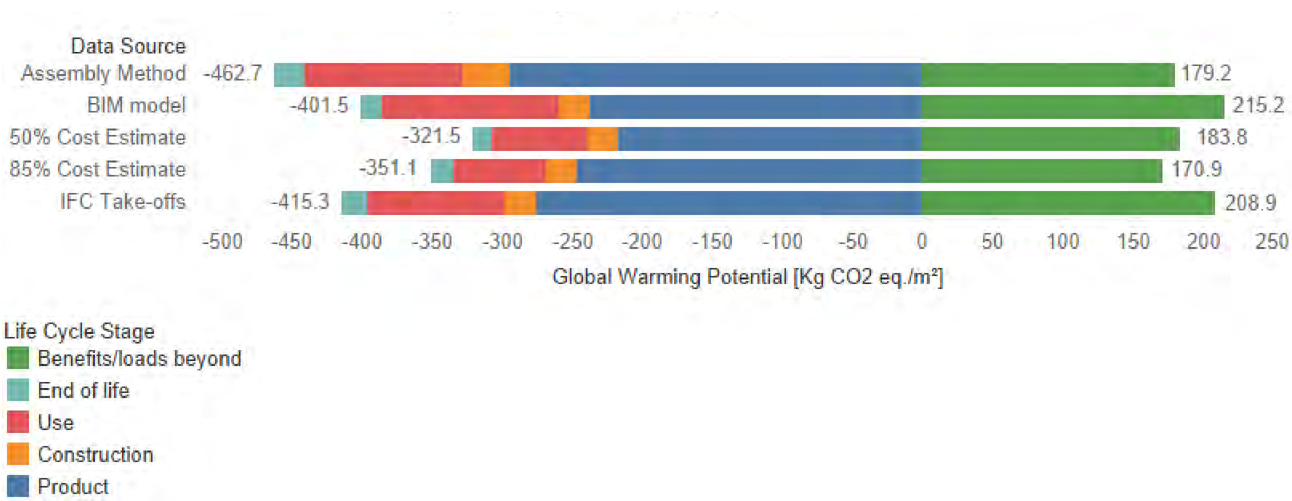

Figure 23: Comparison of the GWP (embodied carbon) impacts of the CEC building estimated through WBLCA using different data sources and BoM calculation methods, and broken down by life cycle stage.

The largest contributing life cycle stage for all of the assessments is by far is the product stage. Emissions from manufacturing and production of materials are generally the highest for that materials life cycle, especially when using prefabricated materials such as mass timbers, steel, and concrete block. This is also where the data is the most robust. Construction activities, and even more so use and replacements, and end of life are highly influences by context and situation, and the data becomes more speculative farther into the future.

The contribution from the use stage is the next largest for all the assessment but also covers the longest period: almost the 100 years of the building's estimated life cycle and all the renovations are likely to take place. The contributions from construction and the end of life (disassembly or demolition) are small, in part due to the limited duration of time compared to the other period.

The benefits and loads beyond the building life cycle, which in this case include both recycling/reuse of materials, such as metal recycling, and carbon sequestration from the large volume of mass timber, are quite significant. They are also of a similar magnitude across all assessments, with relatively minor variations, probably associated with the quantities of specific materials, like wood and steel.

Athena IE does not currently allow for a breakdown of environmental impacts by individual materials, however, a breakdown of BoM and results by major materials categories (as opposed to elements) would be highly informative. The triangulation of major impacts from life cycle stage, building elements and individual materials would help to define specific target area of high or low GWP impacts. This has been identified as future research in Section 4.

3.1.5 Comparison of work time to conduct LCAs from different data sources: Campus Energy Centre

One of the concerns in the development of policies and regulations relying on the use of LCAs, is the time and resources required to collect the data, develop the material quantities, conduct the LCAs and analysie the results. Many of the new LCA tools are marketing themselves in terms of their ease and simplicity of use, as a menas to provide information quickly and cost-effectively to project teams. However, as this report has shown, LCAs, including WBLCAs, are complex and the quality of results is directly linked to the quality and quantity of the input data. A balance has to be found between the appropriate level of input data, staff time/costs, and LCA results that are needed to effectively inform design or policy decisions.

To help inform this discussion, the research team tracked the work time spent on all of the assessments, from the project data collection, through development the BoM and running the LCA. We are seeking to develop a better understanding of which steps in the process were the most time consuming, and where improvements can be made. Additionally, through correlating the work and resources with the GWP impacts results we can start to determine whather there are certain areas that are worth investing more or less resources - more bang for the buck. In this section we are analysing the person-hours of the four major tasks for all of the WBLCA using Athena IE (Assessments 3-7): data extraction from source and processing, material quantities calculations, materials selection and mapping to the material selections in the LCA tool, and data input into the LCA tool to run the LCA. The LCA calculation by the software takes minutes and is not a noticeable part of the total time.

The figures below show the breakdown of hours by tasks for the different assessments based on data sources (Figure 24); the breakdown of hours by tasks for different building elements in the IFC-Drawings-based assessment (Figure 25); and the correlation of people hours and GWP impacts by building elements for the IFC-Drawings-based assessment (Figure 26).

CEC People hours per task across Athena IE assessments

Assessment 7, based on the takeoffs from the IFC-drawings took the longest by far, 288 hours or about 7-8 weeks of full-time work. This is because performing quantity take-offs from project drawings is very time consuming: the data extraction and processing, and materials quantities calculations were the majority of the time. Where it was possible to use a pre-existing BoM, as in the assessments based on BoM from the cost estimates, or where the software was able to export or generate a BoM (or assembly information), as in the assessment using the BIM-model, the time is significantly reduced.

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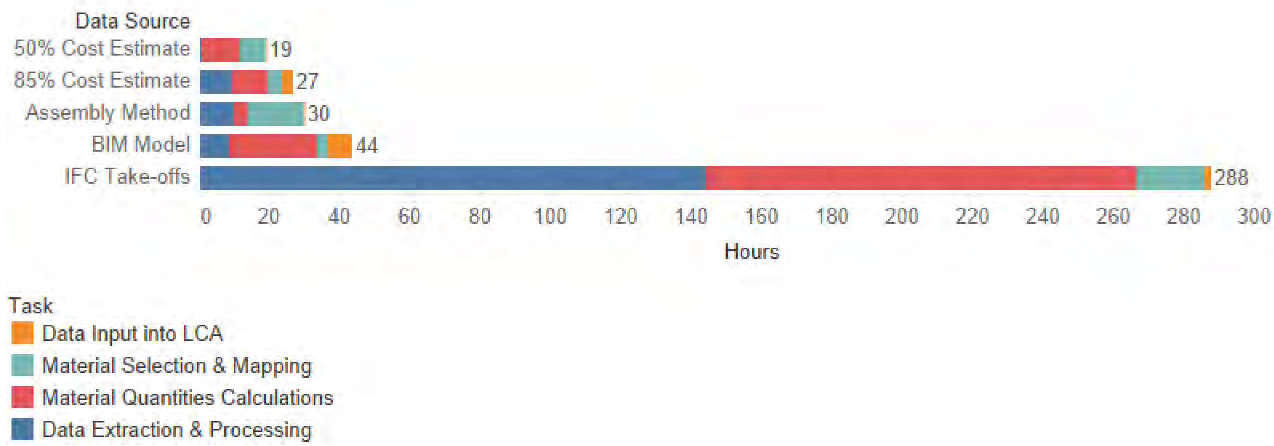

Figure 24: Comparison of people-hours spent creating the BoM and calculating the LCA using Athena IE for the IFC-Drawings-based assessment (Assessment 7).

It should be noted that the quantity take-offs of the IFC and Record drawings were done in-house by the research team, who are not professional quantity surveyors. The time includes a learning curves for staff and students in doing quanitity take-offs, as well as familiarizing themselves with the building in order to understand the information being conveyed through the drawings. A professional quantity surveyor would be faster, but given the wide difference in hours, the IFC based assessment would still have taken more time than the other assessments. The cost consultant's time to develop the BoMs used for the two cost estimates are not included in this comparison, as this information was not available. It would be interesting to get a better sense of the average time and costs associated with creating BoM in standard practice.

The decisions around the mapping of building-specific materials to the materials available in the Athena IE tool were done during the IFC-drawings-based assessment. The research team replicated those decisions for the other assessments (aside from the Assembly-method), so the mapping and selection process therefore required less time. If it needed to be done uniquely for each assessment the proportion of time for this task would be larger. Relatedly, these assessmens were all done within a few months of each other. LCA tools' databases are continually being updated, and the material mapping must take into consideration new information on materials and products, in addition to the specific of new building projects.

CEC People hours per task by building element

Since Assessment 7, based on the IFC drawings, was the most time consuming, we further broke down the total 288 hours to understand which building elements required the most time and resources. Figure 27 shows the breakdown of the total people-hours by tasks, for each of the five major building element categories. The CEC walls required the most time, almost 40% of the total hours, followed by columns and beams, and floors. This division reflects the complexity of the assemblies as the CEC has many wall types, which had to be matched to the plans and sections to determine dimensions and material quantities for each wall layer.

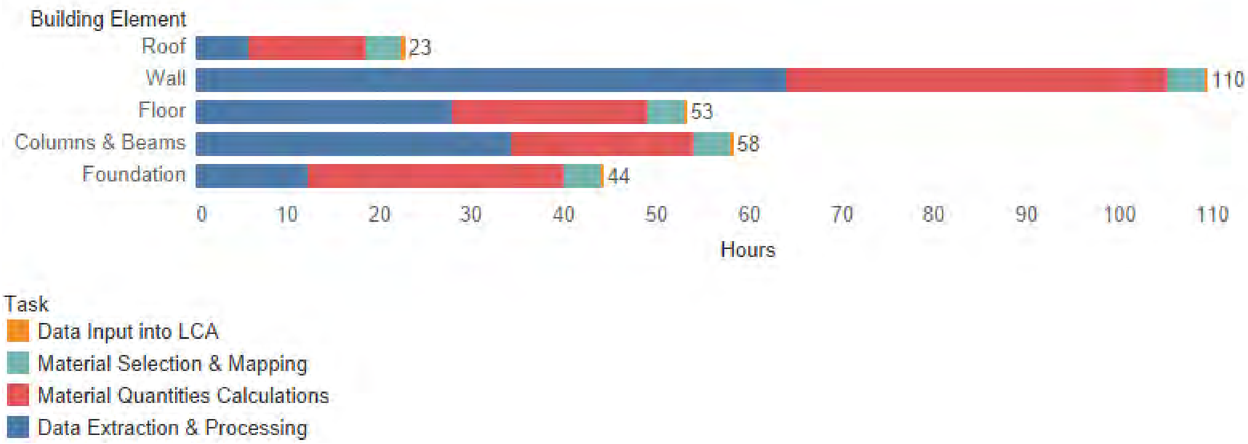

Figure 25: Comparison of people hours spent creating the BoM and calculating the LCA using Athena IE for the IFC drawings based assessment (Assessment 7).

Time allocations by task show that the data collection and material quantity calculations were the most time consuming, across all of the building elements. The are also usually about even, in that it took the research team about as much time to extract and process data from drawings, as it did to calculate materials quanities. It possible that if the research team had either greater familiar with the building design, or greater experience in quantity takeoffs these amounts would be shifted one way or the other.

In comparison, material selection and mapping, and input into the Athena IE tool, required minimal time for all the elements. This reinforces the recommendation to use BoMs that are already created by the project team, provided that the level of detail and accuracy is acceptable. It also shows that while LCA tool developers have done a good job at making their tools user friendly, the bulk of the work to conduct an LCA happens before the data is input into the tool. This is an opportunity for improved guidelines, protocols and other tools to facilitate the translation between building project information and LCA tools. Some suggestions are discussed in Section 4.

Correlation of hours and GWP by building element

To further examine the relationship between time and resources, and results when conducting WBLCA, we compared the people-hours broken down by building elements with the GWP impact of the building elements. Figure 28 shows this comparison of the total time spent on each elements (from Figure 27) with the total GWP impact for each elements (from Figure 24). Generally, the time allocation correlates with GWP impact, so the building elements that required the most time to develop a BoM and conduct an LCA were also the building elements that have the most significant GWP impact.

The walls of the CEC are again the most significant in terms of both hours required and GWP impact, which reflects the complexity of assemblies and concentration of materials in that element. The exception is the floor structure (i.e. the floors, and columns and beams), which took more time to calculate when compared to their relatively GWP impact. These were also some of the custom components of the CEC, using a hybrid of mass timber, steel and concrete, which required more time for the research team to do the quanity takeoffs.

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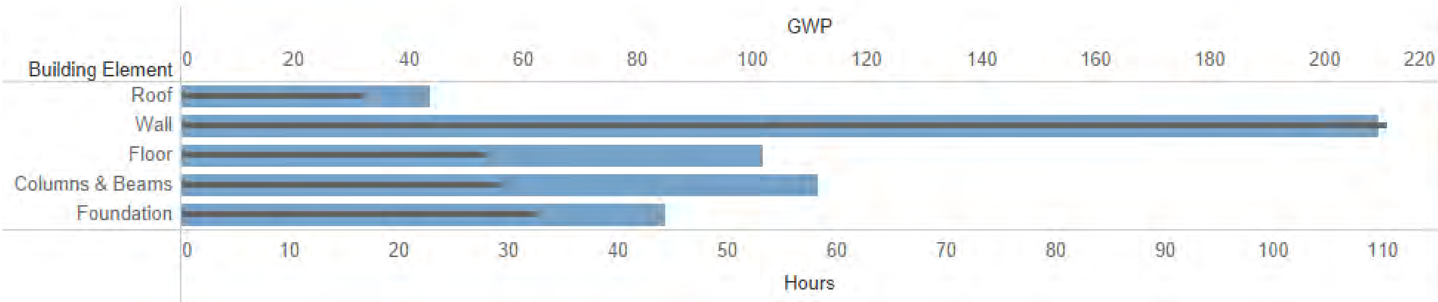

Figure 26: Correlation between the people hours spent quantifying the building elements (shown as the blue bar), and the GWP impacts of that building element (shown as the line) for the IFC based assessment (Assessment 7).

This result, although preliminary, is positive in that it shows the time is generally being put into the right materials and components. It should be noted that this assessment is only for GWP impacts and on a specific building. Different building materials have different magnitude of environmental impacts, and the comparison of hours and impacts may look very different for other environmental impact categories and other buildings.

3.2 IMPACT OF LCA TOOLS ON LCA RESULTS

LCA software tools were created to streamline the process of calculating life cycle assessments. There are a number of tools that have specialized in assessing buildings, which simplify to a certain degree the calculation of WBLCAs to allow for more widespread adoption in the building and construction industry. There are three main LCA software tools currently available for Canada, Athena IE, EC3, and One Click LCA. We used these tools in three WBLCA on the CEC (Assessmnts 7, 8 and 9) all based off of the BoM developed from the IFC and Record drawings.

In this section we compare the total GWP impact results from the three tools, broken down by life cycle stage and building elements, as well the LCA scope for each of the tools and people hours required for each assessment. Our intention is to better understand the variations between the tools, to identify opportunities and constraints that can inform the use of WBLCA to inform policy around embodied carbon emissions.

The following analysis focuses only on the experience with these tools in the Embodied Carbon Pilot, and is not intended as comprehensive description, review or critique of the tools outside of the context of our assessments.

3.2.1 Comparison of assessment scope and databases in different LCA tools

In term of LCA scope, as described in the Assessments in Section 2, these three tools have different system boundaries and include different life cycle stages. Table 30 compares the the lifecycle stages and modules, proscribed by thte tools and included in the three assessment.

Some of this information is contained within the LCA results from each tool. Athena IE includes all the life cycles stages broken down by module, as well as an estimation of external 'benefits beyond the building', such as carbon sequestration and reusability of mateirals. Indiviudal modules can be removed, and a list of the specific inclusions are provided as part of the LCA report. EC3 only includes the product life cycle stage in the LCA system boundary and aggregates the modules (A1-A3) without providing any further breakdown. One Click LCA includes all the life cycle stages, but also aggregates the modules without further breakdown. Additionally, not all materials are included in all life cycle stages in One Click CLA, in Assessment 9 only four materials from the whole BoM were included in the use life cycle stage (B1-B5).

Life cycle stage	Information Module	Athena IE (Assessment 7)	EC3 (Assessment 8)	One Click LCA (Assessment 9)
Product	A1 Raw material supply	X	X	X
	A2 Transport	X		
	A3 Manufacturing	X		
Construction	A4 Transport to the building site	X		X
	A5 Construction-installation	X		
Use	B1 Installed product in use			X*
	B2 Maintenance	X		
	B3 Repair			
	B4 Replacement	X		
	B5 Refurbishment			
	B6 Operational energy use			
	B7 Operational water use			
End of life	C1 De-construction/demolition	X		X
	C2 Transport	X		
	C3 Waste Processing			
	C4 Disposal	X		
Benefits and loads beyond the system boundary	D Benefits and loads beyond the system boundary	X		

Table 30:Comparison of the differences in LCA tools system boundaries from Assessments 7-9.

The three tools also draw on different internal databases of information on the environment impacts of different assessments. Broadly, an LCA (of materials) is a calculation that multiplies the environmental impacts of a unit of a material (as determined through measurements, models or other means), with the quantity of that material. The BoM provides the information on the types of mateirals and quanities. The databases within the LCA tools provide the information on the environmental impacts.

Athena IE is a well established tool, created for North America, an has a relateively large proprietary database of construction materials from Canada and the United States in its library. The environmental impacts of these materials have been drawn from peer-reviewed research, in-house expert estimates, and verified EPDs, for some mateirals product specific information is available, for others only industry averages, or sometimes both. The scope of the assessment can be set by the user.

The One Click LCA's database is composed of publicly available manufacturer-specific EPDs which are used primarily for comparison of environmental impacts from the product lifecycle stage. Some information is provide on other life cycle stages for some materials, supported by in-house and other research. The scope of the assessment is determined by the certification or calculation scheme chosen for the LCA, and the life cycle stages are restricted to match the requirements of the specific certification.

EC3 is the newest tool and was created specific to address embodied carbon emissions in the North American construction industry. The database is composed of product-specific and industry-average EPDs, although at this time the majority of the manufacturer-specific EPDs are for the United States and not Canada. The scope of the assessment is limited to only the product life cycle stage (raw material supply, transport and manufacturing).

A distinctive characteristic of EC3 is that it assigns an embodied carbon range to each material to account for the uncertainty and variation in precision between different EPDs. For each material, they indicate an achievable GWP, which encompasses 20% of relevant EPDs in their database, and a conservative GWP, which encompasses 80% of the relevant EPDs. The conservative GWP is the higher result and can be met by the most products currently available on the market. The achievable GWP is a lower impact and, while possible, can only be met if lower impact products are selected.

Recognizing the variation in assessment scope and types of databases between the tools is critical to understanding the variations in results. A WBLCA including all the life cycle stages will have significiantly higher results than one that only focused on the product stage, for example, but also provides a more complete represenation of the building environmental impacts over time. Similarly, while a WBLCA on a small number of key materials may be appropriate for making design decisions, a relatively comprehensive accounting of building materials is needed to understand the environmental impacts of the whole building.

3.2.2 Comparison of GWP Impacts of LCA tools by building elements: Campus Energy Centre

Technically, do to the varitions in the scope between the assessments within each tool, the results themselves are not strictly comparable. Our comparisons here are less concerned with the specific GWP impacts than in how the variations of results provide a way to explore the different approaches, scope, classifications and databases used by the tools.

Similar to the previous analysis of the Athena IE assessments in Section 3.1, we have broken down the total GWP impacts by building elements to compare the different assessment from the different tools, Figure 27. For EC3, we have used both the conservative and achievable results. The EC3 conservative scenario and One Click LCA results are the highest, and have a similar proportioned breakdown of impacts aacross the building elements (although One Click LCA includes impacts across more life cycle stages thatn EC3, wich only included the product tage). The EC3 achivable scenario is substantially lower, which makes sense since it includes only includes materials with low embodied emissions, and only impacts for the product stage.

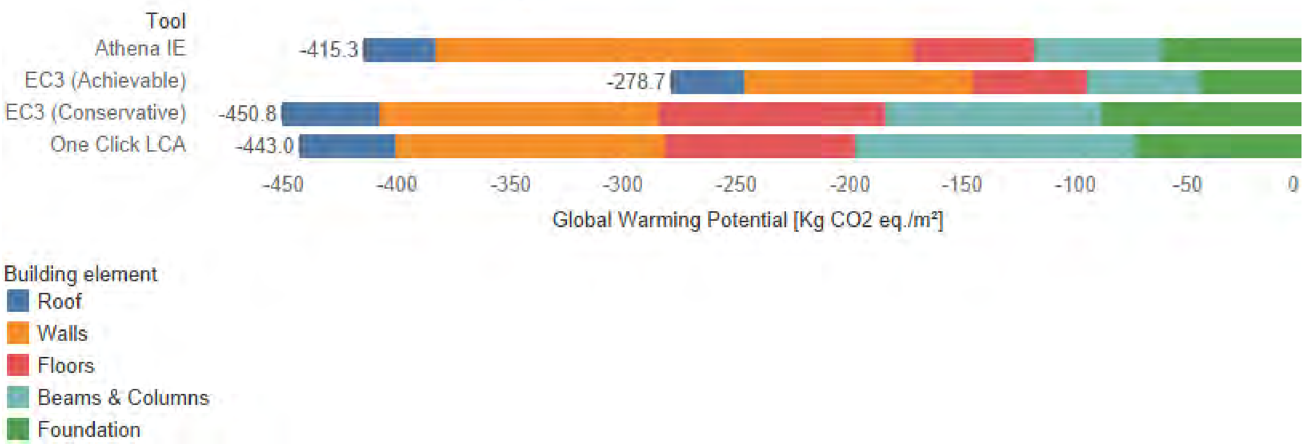

Figure 27: Comparison of GWP impacts estimated using in different LCA tools, broken down by building element.

Selecting the materials in the LCA tools databases that most closely represent the actual materials in the building is critical to ensuring the accuracy of the GWP results. Athena IE's databses had the greatest breadth of materials and was the easiest to use, but the database is composed of general material information that is not location or product-specific, so the results represent more of an industry average, which may be over or under the specific products used in the CEC. By contrast EC3 and One Click LCA both have databases composed of information on specific products. Had the CEC used theose exact products the results would have been more precise. As it was the research team had to make assumptions when selecting the best alternative materials, if actual products were not specified in the project documents or if the specific materials were not available in the tools' databases. Again the results may be higher or lower than the impacst of the actual materials in the CEC.

In addition, each tool follows its own material classification format which initially caused discrepancies when trying to compare the GWP impacts breakdown by building elements. Athena primarily organizes materials according to Uniformat, however, it has additional categories for certain assemblies, such as columns, beams and interior walls, which are not explicitly categorized in Uniformat. EC3 allows users to enter materials according to three different classification systems: Uniformat, Masterformat, or a custom format. One Click LCA does not follow a standard building classification. Instead the tool has four major building groups: foundations and substructure, vertical structures and façades, horizontal structures, and other structures and materials. Within these generic groups, the user can specify further material classification to separate specific assemblies. The researm team attempted to be consistent in the classification of the materials in the BoM between all three tools, but some adjustments were required.

3.2.3 Comparison of GWP Impacts in different LCA tools by life cycle stages: Campus Energy Centre

As the three LCA tools have different systems boundaries a comparision illustrating the results breakdown by life cycle stage is highly informative. Since the data sources is the same for all the assessments, the variations are based on the tools themselves and their database, methodology, and

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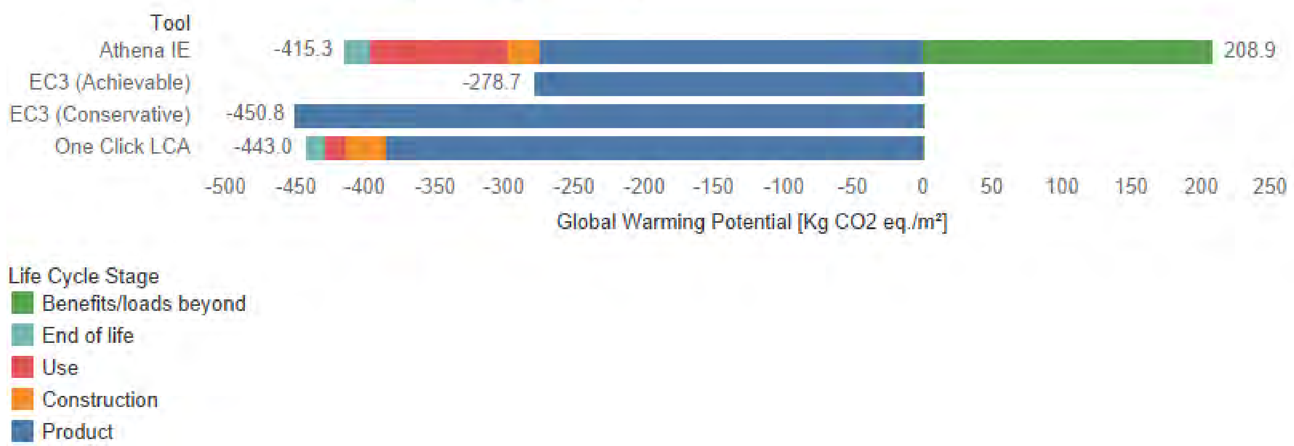

Figure 28: Comparison of GWP impacts estimated using in different LCA tools, broken down by life cycle stages.

assumptions. As with the building elements, we have included both the achievable and conservative GWP imapcst for EC3.

Figure 28 clearly shows the differences in scope between the three LCA tools. While Athena IE and One Click LCA both include all the life cycle stages, the proportions are very different and reflect the databases and approaches used by each tool. As noted above EC3 only estimates impacts from the product life cycle stage, however it is interesting that the achievable impacts from EC3 are similar to the product stage impacts from Athena IE and the conservative impacts are more similar (although higher) than the imapcst from One Click LCA.

Athena IE is the only tool that reports benefits and impacts beyond the building's life, as way to account for some of the trade-offs in mateirals selections. If materials can be resued or recycled, they lower another building environmental impacst, and accounting for positive contributions from materials, such as carbon sequestration is valuable. It should be recognized, however, that the data in this category is more speculative than the rest, both in how benfits are quantified and predictions in how materials may be used decades in the future.

3.2.4 Comparison of people time by LCA tool: Campus Energy Centre

Throughout the LCA calculation process, the research team tracked the time allocated to each task for each assessment. As part of the comparison between LCA tools, Table 31, shows the total people hourse required by the assessment for each tool, broken down by tasks. Since Assessments 7-9 were all based on the same BoM developed from the IFC and Record drawings, the time required to th required to perform the quantity take-offs from the project drawings and calculate the material quanitites for the BoM is excluded. The Table only considers the time spent preparing the data for input nto the LCA tools and for the LCA.

Process	Athena IE	EC3	One Click LCA
Project Setup in Tool	0.5	0.5	0.5
Data Preperation	123	92	76
Data Import	1.5	N/A	
Materials Selection	20	16	5
Data Export	0.5	0.5	0.5
Total	145.5	109	82.5

Table 31: Time allocation to the tasks for calculating the LCAs with the 3 LCA tools (Athena IE, EC3 and One Click LCA)

Project Setup in Tool refers to defining general project parameters such as the name, location, gross floor area, type of construction, and the number of floors. It is both an easy tasks and consistent across all the tools.

Data Preparation includes categorizing the material data from the BoM and converting BoM units to match the material and units used in the tool. This was the most complicated task and took the most time with the most variation for all three assessments.

Data Import refers to uploading the material information into the tool, and is a relatively quick tasks if the dat preparation has been done correctly. Athena IE requires an excel sheet with organized data to be imported which took the most time (1.5 hours). EC3 requires that material selection and quantity inputs be done directly within the tool, so there is not a separate step for inputing data (it's accounted for in data preparation and material selection). Similarly One Click LCA, maps most of the material data automatically and only a few materials had to be input separately from a spreadsheet.

Material Selection consists of mapping the materials used in the building to the materials available in the tool's database. When the exact material does not exist in the database, the user must make assumptions and select an appropriate substitution. This was a complicated task and took the second most time for all three assessment, also with variations across the tools.

Data Export involves exporting the results of the LCA in an organized excel format. A very quick task, which only took half an hour for each.

Overall, LCA using Athena IE took the most time, followed by EC3, and then One Click LCA. Athena IE had the most comprehensive list of mateirals, with the most specificity in material choices and units, which required more manually imput. EC3 and One Click LCA had more flexibility in accepting different in materials and units, and more automated mapping of those input to the information in their databases. This significantly reduces the time for data preparation and materials mapping, compared to input process for Athena IE. One the other hand, it means the user has less control over the process and that the results may not be as accurate for the actual materials in the building.

The first LCA that was completed was using Athena IE (Assessment 7). Therefore, all the material quantities were initially calculated according to the units accepted in Athena IE and mapped to this tool's material database. Because the allowable units in Athena IE were the most specific, this LCA took the most time to complete. This information was then translated to the preparation EC3 and One Click LCA, and reduced the time required for preparation for those tools. Additionally, since the Athena IE LCA was first, it had the most signficiant learning curve which also contributes to the larger hours. All in all, the total differences in time allocations across the tools are substantial and these aspects might only contribute to a small part of the difference.

From this analysis in Table 31 we can also observe that the task of running the LCA through the tool is minimal. More than 98% of the work hours are spent preparing the data to be able to run the assessment, which supports the need for more resources and guidelines for translating information between project documents and information, and the LCA tools.

3.3 IMPACT OF CONSULTANTS ON LCA RESULTS

As part of the comparison of the WBLCAs using different data sources, the research team also reviewed the reports of LCAs conducted by consultants during the schematic design and design development phases of the CEC. There were three stages of design-phase LCAs proposed:

- Stage 1: Comparison of the environmental impacts and life cycle costs of the structural elements alternatives.
- Stage 2: Assessment of the environmental impacts of the envelope and building operation.
- Stage 3: Assessment of the environmental/economic performance of three 60MW natural gas hot water boiler system options.

We were only able to obtain Stage 1 and Stage 2 reports: LCA Study of the UBC District Energy Centre - Hot Water Plant, Stage 1: Structural Elements, dated March 2013, and Stage 2: LEED 2009 MRpc63 Submittal, dated July 2014. The Stage 2 report is also the LEED 2009 Submittal report.

The object of assessment varied between the reports. Stage 1 focused on structural elements only, and Stage 2 included the Stage 1 scope as well as non-structural walls and door/windows fixtures. The assessment system boundary also varied. Stage 1 included only the product and construction phases (A1-A5), and no building life time is noted. Stage 2 included product, construction, and some, but not all, of the use and end of life phases (A1-A5, B2, B4, C1-C2, and C4) and the building life time is assumed to be 60 years.

In addition to the variation in scope, review of the reports revealed variations in data sources and inputs, although both LCAs used the BoM method. The Stage 1 report was based on a BoM developed from materials quantities in the professional preliminary design cost estimate, dated February 2013. This cost estimate was conducted to help the project team choose between different structural material options and dates from about six months before the 50% design cost estimate that created the BoM used in Assessment 5. A spreadsheet of the raw BoM data was included as an appendix to the Stage 1 report. The Stage 2 report did not explicitly list the project data source and only included the BoM output from the Athena IE tool. The Athena IE BoM is not the raw data from the project documents but includes the consultant's assumptions and decisions in order to map the project data to material information in the LCA database, as well as the built in assumptions regarding waste generated during construction and new material required for replacements. As an example, the Athena IE database in 2013 did not include CLT information, so the consultants used environmental information for GLT, as it was the most similar mass timber product in the database. Such substitutions and their rationales are noted in the Stage 1 report, but not in the Stage 2 report (Coldstream Consultants, 2013; Coldstream Consultants, 2014).

Because these LCAs were conducted to answer specific design questions by the project team or to achieve building performance certifications, they were tailored to those needs. However, they also illustrate the challenges of compiling multiple LCAs to inform policy: two LCAs conducted on the same project, by the same consultants, within a very short time frame, had meaningful differences in scope and possibly data sources, because they were created for specific purposes. Without a full understanding of the scope and data inputs, it is hard use the LCA results for anything beyond the original design decisions, and the studies have limited utilitybeyond that singular project and .

As jurisdictions move towards developing policies, such as embodied carbon emissions benchmarking and performance targets, which rely on LCAs for compliance and reporting, the variations between data sruces and approaches become more significant and possibly problematic. While specific LCAs within individual projects can be scoped to answer specific design questions, decisions about portfolios of buildings or certain common typologies require greater consistency and transparency in LCA practices. Section 4 discusses these issues.

SECTION 4.0: CHALLENGES AND LESSONS LEARNED

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4.1 CHALLENGES, TRADE-OFFS AND INFORMATION GAPS

4.1.1 LCA inputs

The accuracy of the WBLCA results is dependent on the accuracy of the project data input into the LCA tool and the accuracy and comprehensiveness of the LCA tool database and assumptions. When assessing the embodied carbon emissions of building materials, aone of the key data input is the quantities of all the materials within the scope of the LCA. Multiple steps are required to prepare the material quantities for input:

1. Collecting and organizing data from project information sources (e.g. if project drawings and specification are the source, the list of materials included in all assemblies and the assembly dimensions).
2. Quantifying the materials (e.g. aggregating materials from different assemblies to create a single quantity for each type of material for each assembly; calculating quantities of materials not detailed in the information sources, like rebar in concrete in architectural drawings).
3. Mapping the building materials to the material library within the LCA tool's database and formatting the input for the specific LCA tool (e.g. matching the naming conventions in the tool or replacing them with a "next best" option if the actual material is not available).
4. Inputting the materials information into the LCA tool, either online or software (the inputs could be BoM that is imported, materials and their quantities that are manually entered, or assemblies and their dimensions and layers that are manually selected and entered. The imported BoM should be reviewed to ensure materials are identified and matched correctly.

The data inputs to calculate the embodied carbon of a building through LCAs, rely on the building's Bill of Materials as the primary data source. Developing a BoM is steps 1 and 2 above. The levels of detail and accuracy of the BoM are dependent on the data source and the quantification method.

Data sources

Project data sources include drawings, models, specifications, cost estimates and other documents that contain project information on materials and dimensions. Project data sources developed early in the building design process will be less accurate than data sources developed when the design is near completion or complete. Early design phase documents or models will include fewer products and materials, and the sizes and quantities of the materials will be based more heavily on assumptions and estimates. Issued-for-construction or record drawings provide more accurate information about the building components and will contain more products and materials, rendered in greater detail.

It can be easier to develop a BoM from earlier phase data sources, since there are fewer components to include, however, it would not be an accurate reflection of the final construction and the resulting LCA would not accurately represent the environmental impacts of the actual building. However, it can provide valuable insight if the objective of the LCA is to inform the building design decisions in order to have a lower embodied carbon footprint. In addition, most environmental impacts come from major building elements, and so it is not necessary to document every minor detail of a building's materials because after a certain level of accuracy, the changes in the results are minimal. The optimal data sources would contain sufficient information on the major components, in a clear and easily accessible format.

BoM calculation methods

The standard way to calculate a BoM is to do a quantity take-off from the project drawings. Quantity take-offs use measurements from the drawing dimensions to calculate quantities of materials. They are standard practice within the building industry and are commonly used as the basis for cost estimates and bids. Quantity take-offs allow for the greatest degree of control over scope (i.e. which components to include or exclude) and directly respond to the accuracy of the data source.

Quantity take-offs are also very time-consuming. Although there are software tools that can assist, quantity take-offs are still largely a manual process, which requires an ability to effectively manage a large quantity of data. Additionally, a certain familiarity with the design is required to interpret the drawings and reconcile discrepancies or fill in gaps of information. There is some subjectivity in how quantity take-offtake-offs are conducted, with room for human error and interpretations, and there are variations between different consultants.

When available, extracting a BoM from a 3D BIM model is faster than a quantity take-off from drawings, however, it is more dependent on the accuracy of the model. Modelling programs, like Autodesk Revit, allow users to directly export BoM created by the software from the information contained in the model. There is less subjectivity in this approach, but also less control and transparency. The internal software algorithms identify the size, shape and properties of the modelled components and categorize them based on a set format. Any information not modelled is not included in the BoM, but programs may also have trouble interpreting or counting certain materials, shapes, or items, especially if modelling 'best practices' are not applied. There are also some LCA software tools that can plug directly into the BIM model to calculate the building impacts, making the process easier but not necessarily more accurate.

Athena Impact Estimator for Buildings has an option to use an Assembly-method input. In this approach, the user selects the types of assemblies and their dimensions within the tool, and the tool itself generates a BoM. This is a straightforward process, however, interface restrictions can potentially affect the BoM by requiring users to select from standardized options, which may deviate to various degrees in specific elements, materials types, or quantities. The deviations are carried through the BoM and LCA results. This input method is useful especially for the preliminary design of a standard building and works better for simplified geometries and common materials because it 'fills in' gaps of information by automatically determining approximated quantities of the missing elements based on conventional assemblies. For example, rebars, nails, and paint are automatically assigned when inputting a foundation or wall assembly. However, when the building design is complete, or if the building has a particularly complex architecture, it is more difficult to specify the design details using this input method.

Lastly, in terms of conducting an LCA, a pre-existing BoM already created for the building project could be used. As mentioned above, BoMs are created for other purposes during the design process and could be repurposed to be used on the LCA. This is the fastest approach, however, it relies on the accuracy of the BoM and its creator. Any subjective decisions or assumptions built into the BoM may or may not be documented, and the ability to identify errors or omissions is limited.

Mapping the BoM to the LCA tool

Once a BoM is developed for a building, the next step is to align the information on the materials and their units of measure with the material selections available in the specific LCA tool. All LCA tools rely on an internal database of information on the life cycle impacts (LCI database) of different materials and products. These databases are frequently updated, but buildings are unique entities, and novel products, materials and construction techniques are continually being developed within the industry, so the specific materials from a building may or may not exist within the database.

LCA tools with larger databases are more likely to have options that either closely match the specific materials, or provide a reasonably next-best option. To create the best fit, material quantities and units sometimes need to be adjusted along with material choices, in order to provide an accurate representation. The choices are largely subjective and require judgement based on familiarity with the building materials, as well as the LCA tool. Even when materials are matched, there can still be variation. Many LCA tool and databases rely on industry averages for many of their materials, which broaden the applicability, but are not as accurate as the specific products.

With the growth of EPDs, new LCA tools such as EC3 and One Click LCA, are building their databases around manufacturer or industry-produced EPDs. In these cases, the tools use the the information on material quanities from the BoM to select appropriate EPDs, as a way to quanitify the environmental impacts. However, the number and quality of EPDs for different types of materials varies widely. Some more common building materials, like concrete, are well represented, while others are not. This means that it can be challenging to match a material and there may not be a “next best” alternative available to choose from. Again, familiarity with both the building and the tool are required to map the BoM to the LCA tool.

Input into the LCA tool

Once the BoM information is mapped and formatted, it is entered into the LCA tool either through an online portal or software application. This can be done manually or as an imported file, depending on the tool requirements. Generally, this is one of the easiest and quickest steps in the process, since the tool interfaces are designed for usability and are easy to navigate. Additionally, there are readily available tutorials, demos and assistance provided by the organizations managing the LCA tools.

Tool developers have focused on the robustness and user interactions of the tools, which is often what is promoted. However, the substantial process described above must be completed before the data can be input in to the tool, and that is where the majority of the time and effort is required, along with subjective decisions and assumptions.

4.2.2 LCA Results

The results from the LCA can vary widely, due to the scope of the assessment and the tools, in addition to the accuracy of the data inputs discussed above.

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LCA scope

The scope of a WBLCA includes the object of assessment and the systems boundary, i.e. the components within the building and the specific lifecycle stages included in the assessment (also known as modules). In order to compare LCA results, as is typically done for a design-phase LCA where the project team is deciding between multiple design options, the scope of assessment must be the same. However, when informing design decisions, the components and lifecycle stages can be as limited as needed, e.g. assessing only two options for the building envelope and only looking at the product and construction phases.

If the LCA is going to be used for setting policy around building performance, such as embodied carbon benchmarking and targets, assessing single building elements and few life cycle stages is not sufficient. A close approximation of the entire building needs to be assessed over the entire life cycle of the building. What constitutes the entire building is open to interpretation, and so is what constitutes the life cycle and the expected useful life of the building. In terms of the object of assessment, there are major elements, such as concrete foundations, that are known to contribute significantly to environmental impacts like GWP, and are an obvious choice to include, but others are more debatable. The quantification of some building elements, such as interior construction and finishes, or some materials such as nails and paint is cumbersome and might not 'move the needle' in terms of embodied carbon assessment. Also, depending on the building design, the distinctions between categories like structure vs walls can be hard to determine, as well as decisions around assigning components to different categories - i.e. gypsum board used as fireproofing could be considered part of the structure or an interior finish.

Establishing the life cycle of a building can be largely based on the LCA tools. Different tools account for different life cycle stages. EC3, for example, only considers the product stage, since the information is based on manufacturers EPDs. Some tools, like Athena IE, consider externalities, such as carbon sequestration in a category referred to as 'benefits and loads beyond the system boundary' since it is a potentially positive contribution rather than a negative impact. Additionally, within tools, the life of the building is able to be set manually. 60 years is a commonly used lifetime, especially in residential construction, but many larger buildings, especially institutional buildings, last longer than that. In principle a complete WBLCA, however, should include allof the life cycle stageswith a reasonable building lifetime for the typology and region.

Usability of LCA results

Extracting LCA results, which come in different forms depending on the LCA tool, as well as organizing them for analysis and decision-making, is an important final step. The results breakdown and formats of different tools can vary substantially. For example, some tools present information through graphs and other visualizations, some limit information that can be exported from the tool, some only report results with a specific breakdown (by material, assembly or life cycle stage), etc. Additionally, while all tools incorporate some degree of built-in assumptions and limitations, there are varying levels of transparency into that information and how it influences the LCA results.

Depending on how the results of the LCA are being used, the format and breakdown of the results and background information, can be important. Percentages are often used in comparisons of environmental impacts, but it is important to also see actual numbers, both for BoM and LCA results. A 50% difference of very small material quantities or impacts is less significant than a 5% difference of very large quantities or impacts. When buildings are being compared, either to reference buildings like in LEED, or to other buildings as benchmarks, transparency is critical to assessing the accuracy of the comparison. The Athena Sustainable Building Institute is currently working on developing a methodology to compare BoMs instead of LCA results when establishing benchmarks, given all the variations and uncertainty associated with calculating an LCA, as discussed above.

4.2 POLICY AND GUIDELINES

Jurisdictions and organizations are beginning to develop policies around the use of LCA as a means to account for, and ultimately reduce, the embodied carbon emissions from their buildings. In order to more effectively use tools like LCAs, policies need to include more specific directions on how to conduct them in order to standardize the data input and the results. The standardization, along with transparency of information and decisions, is critical to building a collection of building projects and information that can be used to develop embodied carbon benchmarks.

When requiring WBLCAs from project teams, policy-makers should provide direction on:

- Standardizing the scope of the assessments, both the object of assessment (which building components are included) and system boundary (which life cycle stages are included) for new construction projects. Ideally a standard could be developed for major retrofits as well.
- Standardizing the data source (including information on the necessary level of design development and option for the types of project documents to use) and BoM calculation methods for input into the LCA tools. Points one and two will help ensure that the material quantities in the resulting BoMare comparable between different projects.
- Standardizing the types, formats and breakdown of LCA results, not through the dictation of specific tools, but by articulating the information needed to inform policy and regulations.
- Expanding the submittal package to include the materials quantities of the actual building, in the BoM, as well as the LCA input and results from the LCA tools.

Because the practice of calculating LCAs for buildings is relatively new, greater guidance is needed to help practitioners navigate the assumptions and decisions that need to be made throughout the process. The decisions made in developing the LCA input are critical to the value of the LCA results, but as discussed in the previous section, are challenging and require trade-offs and familiarity with tools particularities. Guidelines should help project teams balance the detail and accuracy of the LCA with the work time required.

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Corresponding to the policy requirements above, guidelines are needed to support decision-making around:

- Which components should be included in major building elements categories – e.g. what components should be included in 'structure' or 'envelope'?
- The appropriate life cycle stages to include in the assessment and building life time, as well as guidance around the accounting of externalities like carbon sequestration.
- An appropriate level of design development at which to conduct an LCA for embodied carbon performance reporting – e.g. at what point in the project design is there sufficient project information for a useful WBLCA?
- The best BoM calculations methods to use, or if this is established in policy or standards, guidance on how to develop a data source and associated BoM to meet the requirements.
- How to proceed with material selection when mapping the building quantities to the tool database, in particular when exact materials do not exist in the material library, and including additional instructions if the tools rely on EPDs.
- How to track and document assumptions made throughout the data collection and organization, and LCA calculation processes, since these assumption can meaningfully affect the results.

Useful format of LCA results and supporting documentation that should be submitted to the jurisdiction or organization, in order to support the types of policy decision that can be informed by WBLCA. The supporting documents (e.g. building BoM, LCA inputs) corroborates the LCA results, and helps determine how the project can be used in relation to others, e.g. reference building, baselines, part of a statistically valuable benchmark, etc.

4.3 RESEARCH AND NEXT STEPS

The current research in the Embodied Carbon Pilot described in Section 1, 2 and 3 was exploratory by nature. Building on experiences with WBLCAs conducted on two UBC student residences, Brock Commons Tallwood House and Ponderosa Commons Cedar House, we sought to develop a more detailed understanding of the variations within WBLCA as a practice, and the impacts on the environmental impacts, with a focus on Global Warming Potential (GWP), i.e., embodied carbon emissions.

The study used UBC academic buildings, which under the Campus as a Living Lab initiative, are a resource to support applied research and learning. We conducted nine WBLCAs on three buildings, using different project data sources, BoM calculation methods and LCA tools, and comparing the data inputs, results, and work time for the assessments.

4.3.1 Research limitations

The research was limited by the availability of useful project data — we had originally intended to assess 6 different buildings but were unable to secure BoM and other project information for all of them. The architect for the CEC, Dialog, provided a wealth of project documentation that allowed us to conduct different WBLCAs on the same project, and compare them.

We were also limited by team capacity and timelines. The time required to develop quantity take-offs from the First Nations Longhouse and the CEC project drawings was significant, and we did not have the capacity to do more quantity take-offs on other projects within the 1-year timeline of the project. Partly, this is because our team was composed of research project staff and student researchers, who learned on while conducting the current research project. A professional quantity surveyor would have been faster at doing quantity take-offs.

4.3.2 Future Research

The Embodied Carbon Pilot has provided valuable insight into critical areas within the process of conducting WBLCAs in a way that can be used to inform policy, as opposed to design decisions within a single project. The analysis into the influence of data inputs is a step towards developing improved policy direction and guidelines in standardizing the practice. The comparison of tools contributes to the understanding of strengths and limitations, which can inform, in a preliminary way, the best fit for specific types of decision-making.

Additional research into the correlation between the data sources and results is needed to provide greater clarity around which specific building components and materials are major contributors to GWP/embodied carbon emissions. In addition to the GWP impacts broken down by life cycle stages and building elements, a breakdown of GWP impacts by building materials and independent elements would provide valuable information, which some tools provide but not all. Unfortunately, the LCA tool that we used the most in this pilot (Athena IE) does not automatically create this type of breakdown, and it requires additional calculation outside the scope of the standard LCA results. Understanding the intersection of GWP impacts by life cycle stage, building element and materials would help pinpoint major embodied carbon hotspots, which can then be targeted by policy makers and industry.

Additional research into the trade-offs between level of detail from the project data source and ease of developing a BoM and conducting an LCA is needed to find the optimal level of design development at which to conduct WBLCA. This relates strongly with understanding the embodied carbon hotspots and major contributors to GWP. The point in time within the design process when the design of the building's elements that are the major GWP contributes are substantially complete, is when a WBLCA should be conducted to obtain the most useful results. This research can also help inform the scope of an embodied carbon BoM, identifying which components must be included and which are too small to have significant impacts.

The next phase of the Embodied Carbon Pilot intends to follow-up on this work and begin to tackle these issues. Under Phase 2, we intend to conduct WBLCAs on multiple building projects of similar typology: mid-rise multi-unit residential. In the Phase 2 Pilot, we will focus on the practices that inform the development of BoMs, based on data sources from late design development and construction, which can closely represent the finished buildings. We with delve more into the correlations and trade-offs between detailed data source and variation of results, and the intersection of GWP impacts from life cycle stages, building elements and materials choices. As with this first year work, the Embodied Carbon Pilot Phase 2 will inform policy and guidelines in using WBLCA to establish benchmarks and eventually performance targets for embodied carbon in buildings.

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