UBC EMBODIED CARBON PILOT

Study of whole building life cycle assessment processes at the University of British Columbia

THE UNIVERSITY OF BRITISH COLUMBIA
sustainability

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AUTHORSHIPS

This report was prepared by the UBC Sustainability Initiative for the University of British Columbia and Forestry Innovation Investment.

- Angelique Pilon, Director of Urban Innovation Research
- Zahra Teshnizi, Zero Emission Research Manager
- Diana Lopez, Campus as a Living Lab Research Coordinator

UBC Student Research Assistants:

- Krista Kals, School of Architecture and Landscape Architecture
- Mandi Unick, Department of Civil Engineering
- Gavin Pattman, School of Architecture and Landscape Architecture
- Aljhon Lorenzana, Department of Civil Engineering
- Vu Quynh Nhu (Natalie) Nguyen, School of Architecture and Landscape Architecture

The report describes whole building life cycle 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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Cover Image: Campus Energy Centre by Ema Peter, courtesy of Dialog

EXECUTIVE SUMMARY

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 emissions from building materials are becoming proportionally more significant.

Embodied carbon emissions refer to the GHG emissions attributed to materials throughout their life cycle – resource extraction and production, installation, use, and end of life – typically reported in kilograms of carbon dioxide equivalent (kg CO_2 eq). These emissions, along with other environmental impacts, can be estimated through life cycle assessments (LCA), calculations that multiply the environmental impacts of a unit of a material (as determined through measurements, models, or other means) with the quantity of that material used in a building project. Information on the environmental impacts are provided by the assessment tools; information on the material quantity is provided by a project's bill of materials (BoM). Embodied carbon assessments are LCAs that exclude the operational energy and water use and consider only on the embodied carbon emissions from building materials.

The UBC Embodied Carbon Pilot is a multi-year research study on the practice of conducting LCAs to measure a building's global warming potential (GWP), and how they can be used effectively to inform policy and guidelines on embodied carbon emission from building materials, through the establishment of benchmarks and eventually performance targets. The Pilot is being conducted by the Urban Innovation Research team in the UBC Sustainability Initiative (USI), 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.

In order to effectively create benchmarks for embodied carbon emissions in future buildings, policy-makers must have adequate information on the performance of current buildings, which can be used as a reference for baselines and targets. To build a database of existing information, the embodied carbon assessments need to be conducted in a consistent manner, with the same scope and parameters.

The objective of Phase 1 was to explore the process of conducting embodied carbon assessments with the purpose of performance reporting, policy creation, and benchmarking, and to analyze the factors that may affect the consistency, reliability, and variability of results. Factors explored throughout this study include:

1. Availability of project data sources that contain information on the building materials and their quantities.
2. Means of determining which building components and materials should be included in the assessment (object of assessment).
3. Methods of generating a bill of materials (BoM) to categorize and quantify the building's specific materials.

4. Means of determining which life cycle stages are included in the assessment (the system boundary).
5. Selection of the embodied carbon software/web tools that calculate the embodied carbon emissions of the materials and products.

The Pilot leveraged 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. Nine embodied carbon assessments were conducted on three campus buildings: the First Nations Longhouse, the Bioenergy Research and Demonstration Facility (BRDF), and the Campus Energy Centre (CEC), with most of the work focused on the CEC. The scope of the assessments was on major building components – foundation, structure, and envelope – which are generally the most significant contributors to embodied carbon emissions. These assessments used a range of project data sources from different points in design development to generate BoMs and analyzed the variations in both materials quantities and assessment results. Seven of the assessments used Athena Impact Estimator for Buildings (Athena IE4B) as the embodied carbon tool to calculate the building's global warming potential (GWP). Two assessments were conducted using different embodied carbon tools, One Click LCA and Embodied Carbon Calculator for Construction (EC3), to explore variations in system boundary and results due to tool selection. These assessments are described in Section 2 and the analysis in Section 3.

Throughout the Pilot, the processes, assumptions, and issues were documented to better understand the challenges and tradeoffs. In addition, the research team tracked work hours to analyze the breakdown of tasks and the correlation between person hours, project data sources, and the results. A preliminary review of an existing design-phase life cycle assessment (LCA) conducted by a consultant for the project team during the design of the CEC was also included to explore the variations and challenges in using pre-existing LCAs for embodied carbon benchmarking.

When conducting the assessments, the research team found significant variations across the factors described above, each of which required interpretation by the research team and in turn led to variations across results. There was significant variation in BoMs, both in terms of the list of materials and their respective quantities, for the same building based on different project data sources and generation methods. In some cases, the variation reflected changes throughout the design development process, others were based on differences in scope between project data sources or input methods used in the tools. Additionally, translation of the building's materials to align with the tool's material database, as well as the systems boundary and assumptions made within the assessment tool, influenced results. In terms of the results, the embodied carbon impacts were largely consistent when broken down by life cycle stage, with the production 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. However, the proportions of the impacts associated with building elements varied between assessment, and no breakdown by material was possible with the selected tools.

The experience of this first phase of the Pilot illustrated the complexity of conducting embodied carbon assessments, and the extent to which user decisions and assumptions impact both the inputs and outputs of assessment tools. The research provides a better understanding of the challenges, trade-offs, and information gaps encountered by project teams in developing accurate BoMs and the effect that has on the resulting embodied carbon impacts. These findings are discussed in Section 4:

- The accuracy of the embodied carbon assessment results is dependent on the accuracy and completeness of the project data input into the assessment tool and the comprehensiveness of the tool's database, system boundary, and assumptions.
- The purpose of the assessment should drive the decision on what data sources to utilize, since there is substantial variation of results between project data sources and the phase in the design process in which these were developed.
- The BoM is important for an accurate embodied carbon assessment – it needs to be carefully considered and can take significant time and resources to generate depending on the project data source and generation method.
- The comprehensiveness of a tool's material database is as important as having a complete BoM, because this internal database dictates the accuracy in which the BoM can be mapped and assessed by the tool.
- The tool's interface is important for ease of use but inputting the data into the tool requires the least time and resources compared to the rest of the assessment process. Developing the BoM and preparing the information for input require the most time and effort, often with little guidance.
- The assessment scope should be aligned with its purpose (e.g. design decision-making, performance reporting, policy and benchmarking, etc.). For performance reporting and benchmarking, the scope should be comprehensive, which, in practice, is not always consistent and is dependent on data availability and the selected tool's database.
- Assessment results vary widely depending on numerous factors such as scope, data source, BoM generation method, and tool, which means results between assessments are not comparable and have limited usefulness.

Based on the analysis and findings, a preliminary set of recommendations was developed for policymakers to include when requesting embodied carbon assessments on building projects. In order to standardize the assessments and transparency of information in performance reporting and for use in developing benchmarks, policymakers should:

- Clearly define the assessment scope, including both the object of assessment (which building components should be included) and system boundary (which life cycle stages should be included).
- Specify the selection of project data sources and BoM calculations, including information on the necessary level of design development, options for the types of project documents to use, and means of calculating the building's BoM.
- Specify a standard format and breakdown of the results, which should include life cycle stages, building elements and, if possible, materials, not through the dictation of specific tools, but by clearly articulating the information needed to inform policy and regulations.

- Expand the submittal package to include the quantities of materials of the actual building, as well as the input and output of the tools, which show material substitutions, proxies, and additional information added in by the tool. Collecting more detailed packages of information builds a dataset that can be analyzed and studied to identify specific strategies for reducing embodied carbon emissions and inform progressive performance targets.
- Develop guidelines to help project teams navigate the assumptions and decisions that must be made throughout the process, balancing the detail and accuracy of the assessment with the work time required, and help ensure that submittals are consistent with the desired standards.

The Phase 1 work described in this report will be followed with a second phase of the Embodied Carbon Pilot. Phase 2 will conduct embodied carbon assessments on a selection of mid-rise, multi-unit residential buildings, a common building typology in BC. This research will test the recommendations and processes developed in Phase 1, to further explore the effects of project data sources and BoMs on the variation of results, and the intersection of embodied carbon 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 IE4B | Athena Impact Estimator for Buildings

BIM | Building Information Modelling

BoM | Bill of Materials

BRDF | Bioenergy Research and Demonstration Facility

CEC | Campus Energy Centre

CLT| Cross Laminated Timber

CO_2 | Carbon Dioxide

CWF| Construction Waste Factor

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

LCI | Life Cycle Inventory (Database)

Longhouse | First Nations Longhouse

GWP | Global Warming Potential

UBC | University of British Columbia

UoM | Unit of Measure

WBLCA | Whole-building Life Cycle Assessment

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 by-product of construction.

Embodied Carbon Emissions | the GHG emissions, measured in equivalence to CO_2, from the associated with materials and products (as opposed to emissions from operations).

Environmental Impact Category | environmental impact issue being examined, i.e. 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 components 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.

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SECTION 1.0: INTRODUCTION

1.1 BACKGROUND

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 to GHG emissions. Building and construction are responsible for 39% of all global emissions, with operational emissions 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, as indicated above, 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.

1.2 PROJECT OBJECTIVES AND APPROACH

The Embodied Carbon Pilot, conducted by the UBC Sustainability Initiative (USI), is one of the first steps towards developing policy for the embodied carbon performance of buildings. Phase 1 of the multi-year Pilot leveraged UBC's Campus as a Living Lab Initiative, which enables the use of building and infrastructure as for research and learning, to explore the issues and challenges of assessing embodied carbon emissions and create recommendations for policy and practice.

In order to effectively create benchmarks for embodied carbon emissions in future buildings, policy-makers must have adequate information on the performance of current buildings. This enables the establishment of a standard baseline, which can be used to measure reductions, or the development of target rates of embodied emissions for different building archetypes. To build a database of existing information, the embodied carbon assessments need to be conducted in a consistent manner, with a consistent scope and approach, using consistent sources of data.

The objective of the Pilot is to explore the process of conducting life cycle assessments to measure embodied carbon emissions, and analyze the factors that may affect the consistency, reliability, and variability of results. Factors explored throughout this study include:

1. Availability of project data sources that contain information on the building materials and their quantities.
2. Means of determining which building components and materials should be included in the assessment (object of assessment).
3. Methods of generating a bill of materials (BoM) to categorize and quantify the building's specific materials.
4. Means of determining which life cycle stages are included in the assessment (the system boundary).
5. Selections of the software tools that calculate the embodied carbon impacts of the materials and products.

The exploration provides insight on data inputs and resulting estimates of embodied carbon impacts resulting from different types of project information, assessment scopes (building components and life cycles stages), methods of calculating material quantities, and project tools, as well as the tasks and time needed to conduct these types of assessments. Ultimately, the findings of this study can be used to inform the development of guidelines for policymakers and project teams in assessing embodied carbon emissions, and a structured, data-driven approach to embodied emissions benchmarks and targets for buildings.

To achieve these objectives, nine different embodied carbon assessments were conducted on three different campus buildings. The assessments were based on different sources of project data, from different points in the design process, and were assessed using different tools. Throughout the Pilot, the research team iteratively developed processes to try to standardize an approach, and tracked the assumptions, challenges, and gaps of information, as well as workarounds and solutions. The work is described within this report: Section 1.4 describes the methods that were used, Section 2 describes the assessments themselves, Section 3 analyzes variations between the assessments, and Section 4 presents findings.

For the Pilot, USI partnered with the Athena Sustainability Materials Institute, which allowed the research team to draw on Athena's expert guidance, as well as their knowledge of the intricacies of LCA tools and databases. USI also partnered with UBC Campus and Community Planning (UBC-CCP), who provided expertise in policy development, filling 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.

1.3 LIFE CYCLE ASSESSMENT (LCA) FOR BUILDINGS

1.3.1 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a scientific framework that can be used to quantify the 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 life cycle (see Figure 1).

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 scope 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.

Figure 1: Flow diagram illustrating the building life cycle stages and beyond.

1.3.2 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 (CO_2) 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 specific contributions to global warming and for LCA accounting purposes are simplified into a measurement of carbon dioxide equivalent generally reported in kilograms (kg CO_2 eq) in the environmental impact category of Global Warming Potential (GWP).

1.3.3 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 proportional 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 an LCA 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 LCAs focus on major building elements such as structure, foundations, and envelopes, and compare different choices (e.g. mass timber vs. concrete superstructure). LCAs may be used by policymakers to inform policy benchmarks, 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 detail that most closely reflects the actual building. The inputs and 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.

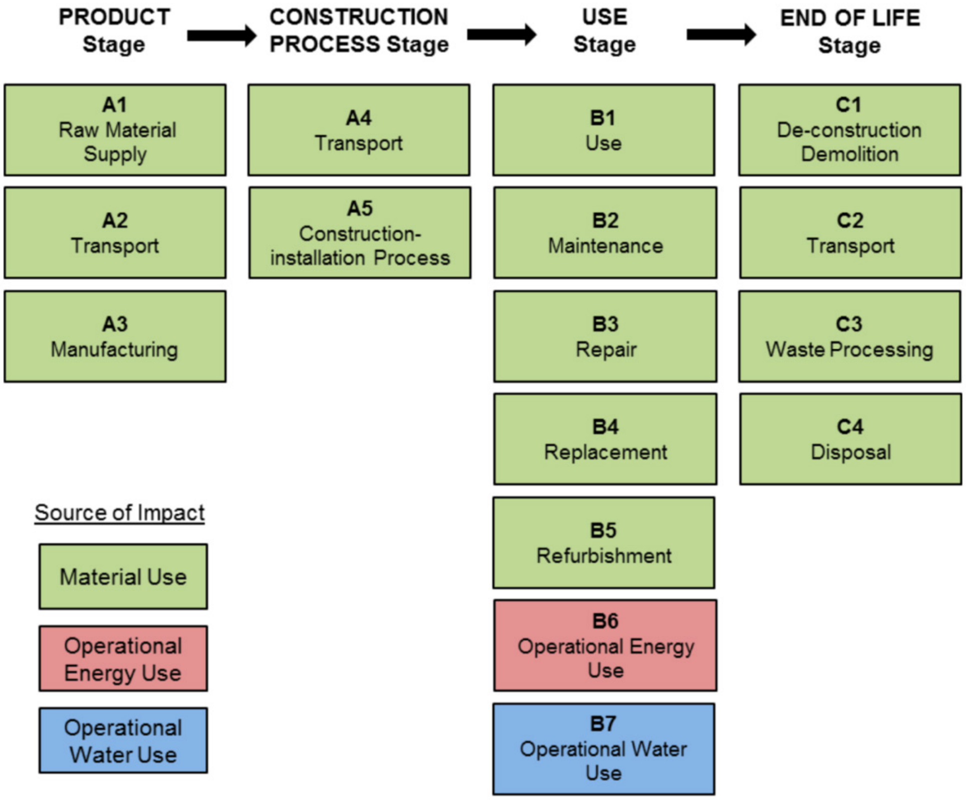

Figure 2: Stages contributing to the embodied carbon impacts over the life cycle of a building (Source: European Committee for Standardization, 2011).

1.3.4 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 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 or their aggregation for use as baselines and benchmarks. 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 of the 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' BoMs, based on high-quality data of the material quantities.

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 database of materials' environmental impacts 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).

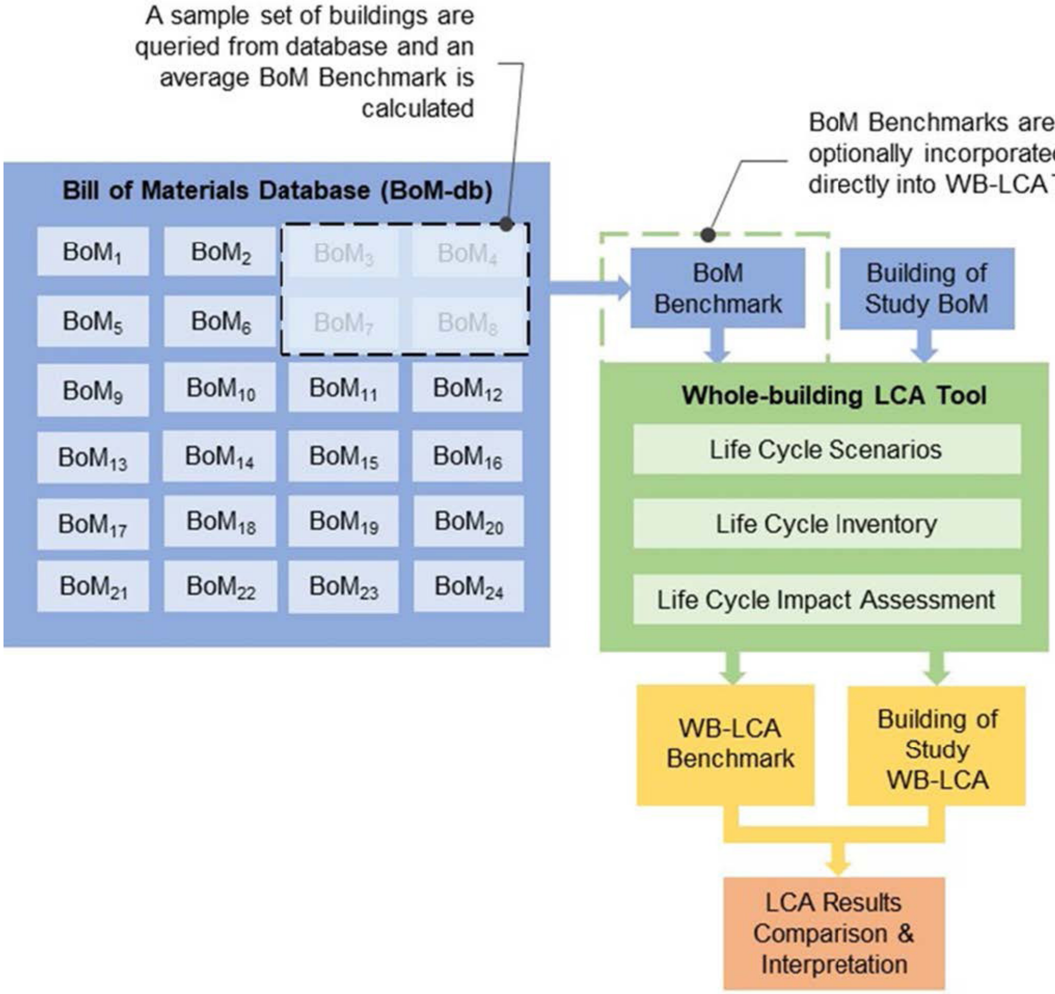

Figure 3: Sampling the BoM to create a benchmark for a proposed building of study (Source: Athena Sustainable Materials Institute,2020).

1.4 METHODOLOGY

1.4.1 Overview of assessments

For Phase 1 of the Embodied Carbon Pilot, embodied carbon assessments were conducted on three campus buildings: the Campus Energy Centre (CEC), the Bioenergy Research and Demonstration Centre (BRDF), and the First Nations Longhouse (Longhouse). The assessments focused on major building components which included the foundation, structure, and envelope. These components generally provide most of the embodied emissions from building materials. Additionally, the research team analyzed the process of conducting the assessments to gain an understanding of the procedural requirements and challenges that should be taken into considerations when developing policies.

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, embodied carbon assessments were conducted based on progressive stages of design development and construction documentation provided by the architect, Dialog, to study the variations in results as the project design was completed. In addition, the assessments were conducted based on the same project documentation, using three different embodied carbon assessment tools to explore the variations in input data, protocols, and results between tools.

As noted above, the research team was guided by Athena's approach to conducting WBLCA by first developing detailed and accurate BoMs. Broadly this involved the following steps:

1. Selecting a shortlist of building on campus to use as pilots.
2. Collecting project documentation from each of those building.
3. Generating input information for the assessment, in the form of BoM and building assembly information, from the project documentation.
4. Organizing the BoM information and running the embodied carbon assessment using online tools to assess the impacts (e.g. Global Warming Potential).
5. Analyzing the outputs to understand variations due to the different project data sources and embodied carbon assessment tools, as well as a process-based analysis of the tasks and time required for different approaches.

This Pilot was exploratory in nature. Embodied carbon assessments were conducted to develop a more detailed understanding of the processes, information requirements and tools in order to identify which factors contributed to variations in results, and located gaps and barriers. As the study advanced, it focused on exploring five variables:

- Project Data Sources: project documentation and models that contain information on the building design, components, and materials and their respective quantities.
- Object of Assessment: building components that are included in the assessment and how to determine whether specific materials are included in those components.
- BoM Generation Method: the protocols to quantify the building materials, categorize the information, and construct a BoM.
- System Boundary: life cycle stages that are included in the assessment and how that decision is made (closely related to the capabilities of the tools).
- Embodied Carbon Assessment Tool: the software tools that calculate the environmental impacts of the materials selection and quantities. These are often WBLCA tools but can also use product information (e.g. Environmental Product Declarations or EPDs) to assess impacts from the product life cycle stage only.

In total, the team conducted nine assessments on the three buildings, using different project data sources and embodied carbon assessment tools, as shown in Table 1. The different project data sources and tools meant that there were differences in the BoM calculations methods, object of assessments and systems boundaries, all of which contributed to variations in the results. These assessments are described in detail in Section 2.

PROJECT DATA SOURCE	EMBODIED CARBON ASSESSMENT TOOL	BUILDING		
		First Nations Longhouse	**Bioenergy Research and Demonstration Facility**	**Campus Energy Centre**
BIM model	Athena IE4B			Assessment 3 & 4
Cost Estimates			Assessment 2	Assessment 5 & 6
Project Drawings		Assessment 1		Assessment 7
	EC3			Assessment 8
	One Click LCA			Assessment 9

Table 1: Assessments conducted on three UBC buildings using different project data sources and embodied carbon assessment tools.

1.4.2 Building Selection and Data Collection

Since this research project was intended to be exploratory, with input from UBC-CCP, a shortlist of buildings was selected with different functions, sizes, and designs, as well as different consultant teams. Initially, six UBC buildings were selected:

- The Bioenergy Research and Demonstration Facility
- The Campus Energy Centre
- The Baseball Indoor Training Centre
- The Engineering Student Centre
- The First Nations Longhouse
- 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 eight 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 in partnership with the Athena Sustainable Materials Institute.

Ideally, construction cost estimates with a detailed BoM for each building would have been collected. However, UBC manages project costs in a specific manner that does not typically include the production of a construction cost estimate using quantity surveying. Therefore, the research team sought to collect an array of project documentation from UBC Records, as well as the primary consultants from each building, to generate the BoMs. The project documentation collected, referred to in this report as project data sources, include:

- Architectural and structural project drawings: record or as-built drawings where available, alternatively issued for construction (IFC) or issued for tender (IFT) drawings.
- Cost estimates with material quantities, calculated at different design development stages.
- BIM or 3D virtual models at different levels of design development.
- Existing LCAs conducted by the project team or their consultants.

Not all the information was available for each building project. The availability of good quality information was the primary limiting factor in conducting the LCAs efficiently. After preliminary studies on the Longhouse and the BRDF, focus was put on the CEC, since multiple project data sources from different design stages were successfully collected. 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, no additional buildings were analyzed. Table 2 shows the details of the project data sources collected and used for each assessment.

ASSESSMENT	BUILDING	PROJECT DATA SOURCE	PROJECT DATA SOURCE DETAILS	DOCUMENT DATE	CONSULTANT	DESIGN DEVELOPMENT
1	LONGHOUSE	Project Drawings	Architectural IFC drawings Post-tender Addendum #1	Feb. 28, 1992	Larry McFarland Architect	100%
			Structural IFC drawings Post-tender Addendum #1	Feb. 28, 1992	CWMM	100%
2	BRDF	Cost Estimates	Preliminary Cost Estimate Draft for Review (design options)	Aug. 12, 2009	JBA	Conceptual design
3,4	CEC	BIM model	Architectural Revit model Issued for 80%	Oct. 24, 2013	Dialog	80%
			Structural Revit model Issued for Permit	Nov. 8, 2013	Dialog	80%
5	CEC	Cost Estimates	50% Drawings Estimate	Sept. 6, 2013	Hanscomb	50%
6	CEC	Cost Estimates	85% Costing Report	Dec. 16, 2013	Hanscomb	85%
7,8,9	CEC	Project Drawings	Architectural record drawings	June 29, 2016	Dialog	100%
			Structural IFC drawings	June 17, 2014	Fast+Epp	100%

Table 2: Project data sources used for each assessment.

1.4.3 BoM Generation Methods

There are multiple ways in which a BoM can be created depending on the project data it is sourced from and the tools to generate it. In this Pilot, four BoM generation methods were explored:

- Quantity takeoffs estimated by the research team from project drawings.
- Material quantities listed in cost estimates developed by project consultants.
- Material quantities exported from BIM software (e.g. Autodesk Revit) developed from geometric and volumetric information contained in a BIM model.
- BoM generated by the Athena IE4B tool based on building assembly information derived from project data sources and input into the tool by the research team (referred to in this report as "assembly method").

For the First Nations Longhouse, the BoM was developed using the first method, material quantity takeoffs using the IFT drawings. Since the project dates from the mid-1990s, most of the project drawings were hand drawn, and the research team measured the PDFs using Bluebeam Revu software and calculated the BoM manually. In addition, an LCA through the assembly method in the Athena IE4B tool was conducted using the materials and geometry from the IFT drawings to assign assembly categories for the components of a selected exterior wall.

For the BRDF, a BoM was derived from material quantities in 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 the material quantities of major components. While the research team collected IFC drawings of the BRDF, due to time constraints, the development of a detailed BoM based on quantity takeoffs from the drawings was not pursued after the decision was made to focus on the CEC.

For the CEC, five different BoMs were created using the four methods outlined above: one using quantity takeoffs from the project drawings, two from materials quantities listed in the cost estimates created at 50% and 85% design development, and two based on materials information exported from the partial BIM model (architectural and structural Revit model created around 80% design development). For the last two BoMs, one was exported directly from the Revit software, and the other one was generated by Athena IE4B's assembly method, based on the inputting of materials and geometric information from the BIM model.

In a BoM the specific materials are organized into categories based on different classification systems in use within the building industry. Two common systems are: MasterFormat, which is mostly used to organize construction data and cost by trades, and UniFormat, which is mainly used for classifying building material quantifications and cost estimation during design development. A third system, OmniClass is a comprehensive classification system for the construction industry that incorporates both MasterFormat and UniFormat. OmniClass is relatively new and not as widely used as the other two. In this Pilot, the UNIFORMAT II classification system was used throughout all the BoM to align with the classification system format from the collected project data sources.

1.4.4 Embodied Carbon Assessment Tools

There are multiple embodied carbon assessment tools available to the building industry. Many of them are WBLCA tools that assess a number of environmental impacts, one of which is embodied carbon emissions or GWP. More recently, as there has been a growing focus on GHG emissions reduction in response to climate change mitigation targets, new tools are emerging focused specifically on the carbon emissions of buildings and the embodied carbon emission of materials and products. These tools all have their own databases of material and product information that contains the data on the embodied carbon or other environmental impacts. These may be public or proprietary, use industry-average and/ or product-specific information, and have varying degree of regional specificity. In many cases, they are supported by the development of Environmental Product Declarations (EPDs), statements from manufacturers or industry about the GWP of their products.

This Pilot includes assessments using three different embodied carbon assessment tools: the Athena Impact Estimator for Buildings (Athena IE4B), One Click LCA, and the Embodied Carbon in Construction Calculator (EC3). As this project was exploratory and also of limited duration, the goal was not to conduct a comprehensive comparison of different available tools. Tools selected were representative of some of the range of available tools in their use of different data sources and their assessment scope, and which were known from past discussions with consultants and policymakers to be of interest to the local industry.

Athena Impact Estimator for Buildings (version 5.4) is a tool developed by Athena Sustainable Materials Institute and assesses environmental impacts across all the life cycle stages of a building. This software tool is currently one of the most commonly used WBLCA and LCA tools in North America. It draws on an in-house Life Cycle Inventory (LCI) database with about 200 construction materials from Canada and the U.S.A. While the majority of Athena's LCI is based on industry-averages, it is regionally sensitive. This means it takes into account variations in manufacturing technology, transportation and electricity grids in different regions. The Athena IE4B lets users compare the relative environmental effects or trade-offs across alternative building design solutions at the conceptual design stage. From an input perspective, the assembly method allows users to enter key building descriptors and select from an array of building assemblies to describe a three-dimensional structure. The tool also supports the input of a pre-estimated BoM by allowing users to import BoM information directly from Excel files (Athena Sustainable Materials Institute & Morrison Hershfield, 2020).

One Click LCA (Database version 7.6) is an online WBLCA tool developed by Bionova Ltd. for the European market and has recently been adapted to North America. The tool draws on a combination of 65,000+ public and private industry-average and manufacturer-specific EPDs which are reviewed and verified in-house, and in-house developed data and methods to fill the local EPD and other data gaps. For the North American context, the software relies on One Click's generic database as well as a number of publicly available European and International EPD databases. The tool allows for comparison of the product stage environmental impacts, and when the information is available in the EPDs, the other life cycle stages including construction, use and end of life. It is intended to align with green building rating systems, and uses an algorithm which defines the data selections available to the users based on the requirements of specific certifications (Bionova Ltd., 2020).

Embodied Carbon in Construction Calculator (version v-22.1.1_b-1302) is a new open-source online tool supported by the Carbon Leadership Forum and conceived by Skanska USA and C Change Labs. It is an embodied carbon assessment tool, not an LCA tool, and is focused on supply chain liability and specifically targets embodied carbon emissions from the production of building materials. Therefore, it is intended to inform material selection and procurement decisions using product stage impacts, not the impacts of the building throughout its life cycle, and only in embodied carbon emissions, not other environmental impact categories. The tool relies on the materials quantities entered by the user from project documents and draws on a database of 26,000+ EPDs, with a focus on significantly growing the product-based EPDs rather than the industry-average EPDs (Carbon Leadership Forum, 2020).

Assessments 7-9 assess the CEC and are all based on the same BoM derived from the IFC and record drawings, but each was conducted using a different tool from the described above. Since consultants are using different types of tools, the research team was interested in developing a better understanding of the variations in processes between different tools, based on their different databases and system boundaries, and assessing the variations in user experience and reported results even when using the same project data sources and BoM.

1.4.5 Pilot Scope

The scope of the assessments in the Pilot focused on major building components and was kept consistent across all assessments as much as possible. The 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 therefore are the most useful in terms of benchmarking and impact reduction. They are also highly likely to be assessed in design-phase LCAs 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, specific elements were excluded 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 life cycle stages and modules in each assessment, the system boundary, vary depending on the tool used for the assessment. The modules assessed in Athena IE4B, which was the primary tool used, are detailed in Table 3 and include the extraction and production (A1-A3), construction (A4-A5), use (B2, B4) and end-of-life (C1-C2, C4) stages. Athena IE4B also assesses benefits beyond the life of the building (D), which includes beneficial characteristics of building materials choices, such as carbon sequestration and recyclability. Operational energy and water use can also be assessed by the Athena IE4B, and are commonly included in a WBLCA to get a comprehensive picture of the environmental impacts, but were excluded from the scope of this study since the objective was to assess only the embodied carbon emissions from the buildings' materials.

Information Module	Processes Included in Athena IE4B
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 to building site	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 IE4B system boundary for Assessments 1-7 (Adapted from “Project Report LCA results” generated by the Athena IE4B tool - version 5.4).

EC3 relies on a database of industry-average and product-specific EPDs, which mainly contain information sourced from product manufacturers. The tool only estimates material impacts from the product life cycle stage (Table 4); it cannot be used to do WBLCAs and is generally used for design and procurement decisions.

Information Module	Processes Included in EC3
A1 Raw material supply	Extracting raw materials (or for processing recycled materials)
A2 Transport	Transporting materials to and from the production facility
A3 Manufacturing	Manufacture products from raw or recycled materials

Table 4. EC3 system boundary for Assessment 8 (Adapted from “Embodied carbon in the EC3 tool: Beta methodology report”, Carbon Leadership Forum, 2019).

One Click LCA relies on manufacturer EPDs for information from the product life cycle stage (A1-A3) and disposal (C4). The rest of the stages (A4-C3), which are determined at the building level rather than at the product level, are calculated in accordance to European Standards (in accordance with Section 5 of the BRE Briefing Paper "Assessing the environmental impacts of construction – understanding European Standards and their implications.") and shown in Table 5. One Click LCA supports calculation of all life cycle stages, however, not all life cycle stages are calculated by default and therefore require relevant input from the user. The system boundary is limited by the certification or calculation scheme chosen for the assessment. For Assessment 9 in this Pilot, the stages included were the extraction and production (A1-A3), transport to building site (A4), use (B1-B5) for only a few materials, and end-of-life (C1-C4) stages. As mentioned before, operational energy and water use were excluded from this study since only embodied carbon emissions from the building's materials were assessed. This tool uses an internal protocol to adapt their data to the regions where there are significant data gaps, which still includes Canada.

Information Module	Processes Included in One Click LCA based on:
A1 Raw material supply	Material data point
A2 Transport	
A3 Manufacturing	
A4 Transport to building site	User given distance and transport method OR user-confirmed region defaults
B1 Installed product in use	Via data domain defaults or material specific data points
B2 Maintenance	
B3 Repair	
B4 Replacement	Via service life either set by the end user or user-confirmed defaults
B5 Refurbishment	
C1 De-construction demolition	Regional scenario
C2 Transport	
C3 Waste processing	Material properties and regional scenario
C4 Disposal	

Table 5. One Click LCA system boundary for Assessment 9 (Adapted from "Quality and consistency for whole-building LCAs using product-specific EPDs" (One Click LCA, 2018).

1.4.6 BoM Calculation and Assessment Process

Throughout the Pilot, standardized processes were developed to generate the quantities of materials, develop BoMs and conduct the assessments. An overview of the general process that was followed to calculate all the assessments, with some variation depending on the project data source and specifics of each building, is outlined below. Since seven of the nine assessments were done using Athena IE4B, the process is described with that tool as the default. The assessments using One Click LCA and EC3 were based off of the same BoM developed for use in Athena IE4B and are noted in step 4 below.

1. Project data extraction and processing. The building's material quantities were extracted from the project drawings, BIM models, or cost estimates. In the case of project drawings, the research team used Bluebeam Revu software to calculate the material quantity takeoffs. The project drawings were all in PDF format but varied between scanned (rasterized) PDFs or vector-based PDFs converted directly from drawing files, which are more accurate for dimensioning. From the BIM models, the material quantities were calculated by the software's algorithms based on the components and geometries in the model. The material quantities were then classified and organized in Excel.
2. Material quantity calculations. The quantities were organized into categories, with any necessary calculations performed to convert dimensions into the appropriate unit according to Athena IE4B (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 Athena'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 IE4B also required the incorporation of two factors: the Construction Waste Factor, intended to account for on-site construction waste, and the Unit of Measure (UoM) Multiplication Factor, which converts the imported material quantity to the units in the Athena database. The Construction Waste Factor is a set percentage calculated by Athena IE4B that is added to individual material quantities, then rolled into the BoM. It is added automatically in the assembly method, and so the research team chose to incorporate it into the rest of the assessments for consistency and comparability. The UoM Multiplication Factor is only applied when inputting the BoM directly and is not used in the assembly method. The research team accounted for most of the unit conversion when calculating quantities but some materials in the database had set dimensions (e.g. given thicknesses of sheet materials) that required the research team to make additional adjustments to accommodate.
4. Data input into Athena IE4B. A new simplified Excel data table was created to match the Athena IE4B inputs requirements, including the Excel columns' naming 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 One Click LCA, similar to Athena IE4B, a simplified Excel data table is used to prepare materials for input. One Click 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 II, MasterFormat, or a custom format.
5. Results output and synthesis. The results from the LCA tool were exported to an Excel spreadsheet and prepared for analysis.

6. Assessment results breakdown by building elements and life cycle stages per m^2. The GWP impacts for each assessment were divided by the gross floor area of the building (sourced from the UBC Infrastructure Development Records) to visualize the results per m^2. These results breakdowns were used to examine which building element or life cycle stage were the primary contributors of embodied carbon emissions. The results were analyzed by the research team, to explore the variations depending on project 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 assessments to identify the most time-intensive activities. The results of this analysis are described in greater detail in Section 3.

The process-based analysis used in the Embodied Carbon Pilot provides insights into the types of project data sources, material quantity calculations, tools, expertise, and work required of project teams and consultants in order to assess the embodied carbon emissions from their building materials. Policymakers must take these factors into consideration when developing guidelines and compliance pathways around the use of WBLCAs and other embodied carbon assessments in development projects.

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-story, two thousand square metre, heavy 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 center for First Nations, Metis, and Inuit faculty, students, and staff.

Within the building are offices, seminar rooms, a resource center, 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 shiplap plank exterior cladding and a copper roof (UBC, 2013).

The Longhouse was completed in 1992, so the amount of project information available to the research team was limited. The main project data source for the WBLCA was the IFC architectural and structural drawings. Quantity takeoffs were conducted on the main building elements, including foundation, structure, and envelope to create the building's BoM. To estimate the Longhouse's embodied carbon emissions, a WBLCA was conducted based on the BoM using the Athena IE4B tool (Assessment 1).

The research team also attempted to run a WBLCA by inputting the building assembly information into the Athena IE4B using the assembly method detailed in Section 1.4. The assembly information, such as dimensions, assembly geometry, and materials, was sourced from the building's IFT/IFC drawings and the quantity takeoffs estimated for Assessment 1. However, the assembly method in Athena IE4B is intended for buildings in the conceptual design stage, and defining assemblies of an existing building accurately using this input method proved challenging. In addition, the building's unique structure added to the complexity of the task. Therefore, only two walls were assessed using the assembly method, in order to quantify the difference in material quantities from these two methods. The details of this analysis can be found in Section 3.1.

Photo of First Nations Longhouse, credit Don Erhardt

2.1.1 Assessment 1 – WBLCA using BoM from IFT Drawings

Assessment 1 consists of a WBLCA on the First Nations Longhouse based on the building's BoM and using the Athena IE4B. The BoM was generated by the research team using material quantities derived through quantity takeoffs of the project's IFC architectural and structural drawings. In this case, quantities were estimated from scanned PDFs of hand drawings, which required additional interpretation from the research team. The WBLCA was calculated based on the methodology outlined in Section 1.4 and included the timber structure, concrete foundation, exterior walls, and roof.

BUILDING: First Nations Longhouse

GROSS FLOOR AREA: 2,226 m^2

PROJECT DATA SOURCE

Architectural and structural IFC drawings: (Post Tender Addendum#1; February 28, 1992)

BOM GENERATION METHOD

Quantity takeoffs from project drawings

ASSESSMENT TOOL

Athena IE4B (Version 5.4.0101)

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

Building Element (Modules A-C)	Global Warming Potential [kg CO_2 eq/m^2]	Impact Contribution [%]
Roofs	26.4	14%
Walls	82.7	43%
Floors	1.3	1%
Beams & Columns	23.6	12%
Foundations	58.4	30%
Total	192.4	100%

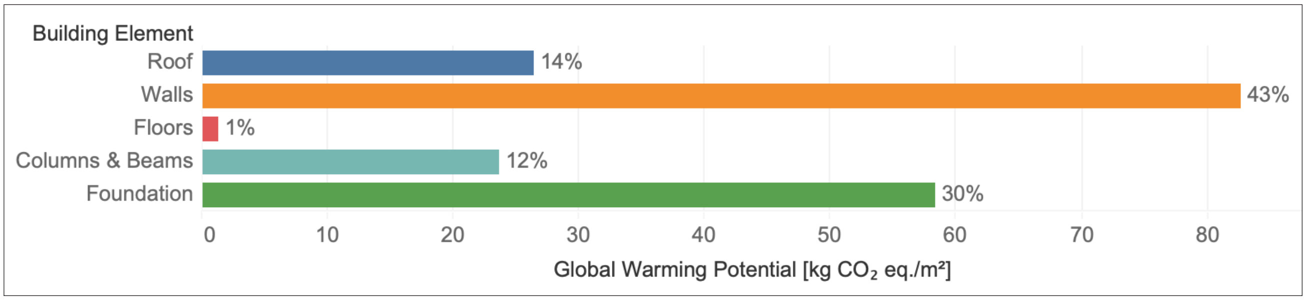

Figure 4 and Table 6: Assessment 1 results, breakdown by building element.

Assessment 1 - Results

Assessment 1 estimates that the Longhouse has a total GWP impact of 428,282 kg of CO_2 eq, or 192.4 kg of CO_2 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 shiplap or planks with wooden detail strips, plywood sheathing, moisture/vapor/air barrier, batt insulation, wood studs and framing, and gypsum wallboard or interior cedar finish.

This building is one storey, with a small mezzanine. The mezzanine floor structure and concrete topping, which account for only 6% of the building's gross floor area, were categorized as floors in the Athena IE4B tool. However, the floor structure for the ground level was categorized as foundation, since it is a slab on grade. This difference in categorization results in a very low GWP impact for floors (1%) compared to the impact for the foundations (30%).

In terms of the building life cycle, almost half of the Longhouse's GWP impact is generated in the product life cycle stage (49%), followed by the use stage (38%). These two stages are the most production intensive for materials. Since the primary material for the superstructure is heavy timber, the carbon sequestration and the benefits beyond the building life cycle are quite high (77%), with the potential of offsetting most of the building's total impacts.

Life Cycle Stage	Global Warming Potential [kg CO_2 eq/m^2]	Impact Contribution [%]
Product (A1-A3)	94.2	49%
Construction process (A4-A5)	12.3	7%
Use (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%

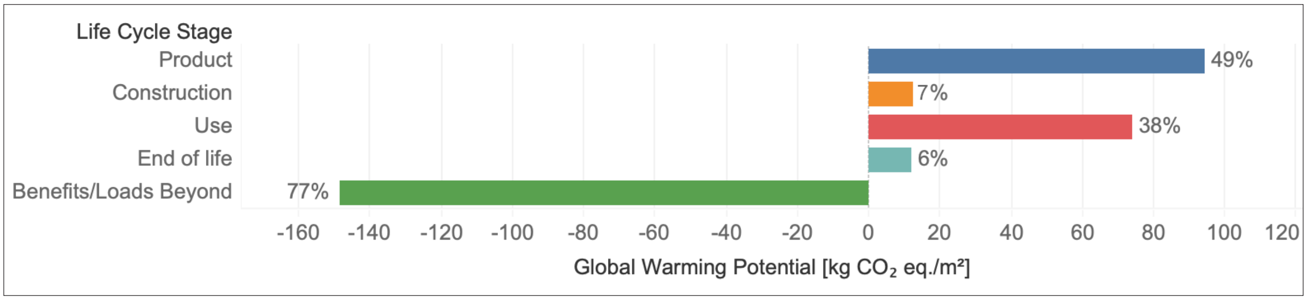

Figure 5 and Table 7: Assessment 1 results, breakdown by life cycle stage.

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 campus' 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-head section houses the energy generation system, and a mezzanine area includes offices, labs, and a public viewing space.

The BRDF is one of the first industrial buildings in Canada to be constructed with cross-laminated timber (CLT) panel technology. The exposed mass timber structure is composed of CLT panels for the walls, floors and roof decking, and glue-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 project data sources available for a WBLCA of the BRDF were the architectural and structural as-built drawings, and a conceptual 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 quantities from the cost estimate to develop the BoM and conduct a WBLCA on this building using Athena IE4B (Assessment 2). This allowed an assessment of 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

BUILDING: BRDF

GROSS FLOOR AREA: 1,950 m^2

PROJECT DATA SOURCE

Conceptual design cost estimate

(Preliminary Cost Estimate – Draft for review; August 12, 2009)

BOM GENERATION METHOD

Material quantities from cost estimate

ASSESSMENT TOOL

Athena IE4B (Version 5.4.0101)

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

2.2.1 Assessment 2 – WBLCA using BoM from Preliminary Cost Estimate

Assessment 2 consists of a WBLCA on the BRDF, calculated using a preliminary BoM through the Athena IE4B tool according to the methodology outlined in Section 1.4. The assessment includes the structure, foundation, envelope, and roof. The BoM was developed based on the material quantities in a conceptual 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 CO_2 eq/m²]	Impact Contribution [%]
Roofs	41.8	10%
Walls	94.4	23%
Floors	2.9	1%
Beams & Columns	44.6	11%
Foundations	227.2	55%
Total	410.9	100%

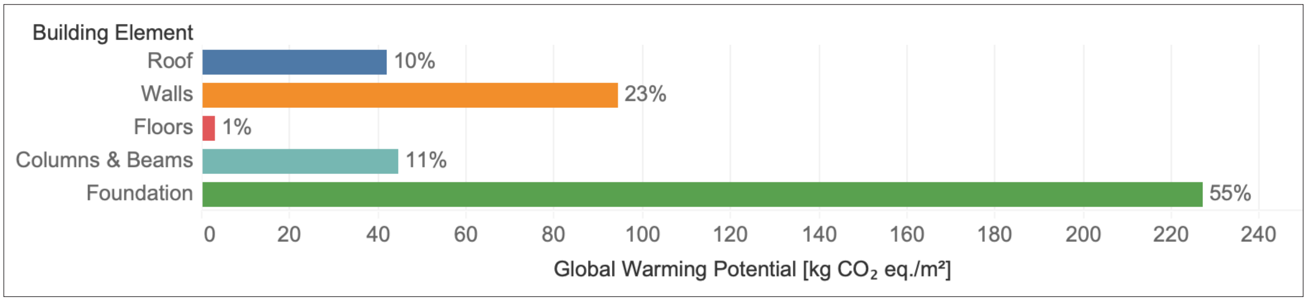

Figure 6 and Table 8: Assessment 2 results, breakdown by building element.

Assessment 2 - Results

Assessment 2 estimates that the BRDF has a total GWP impact of 801,311 kg of CO_2 eq, or 410.9 kg of CO_2 eq per m². 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 (34%) of the total GWP.

The majority of the GWP impact is generated in the product life cycle stage (73%), which is a relatively standard finding of materials' life cycles. 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 CO_2 eq/m²]	Impact Contribution [%]
Product (A1-A3)	297.9	73%
Construction process (A4-A5)	28.4	7%
Use (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%

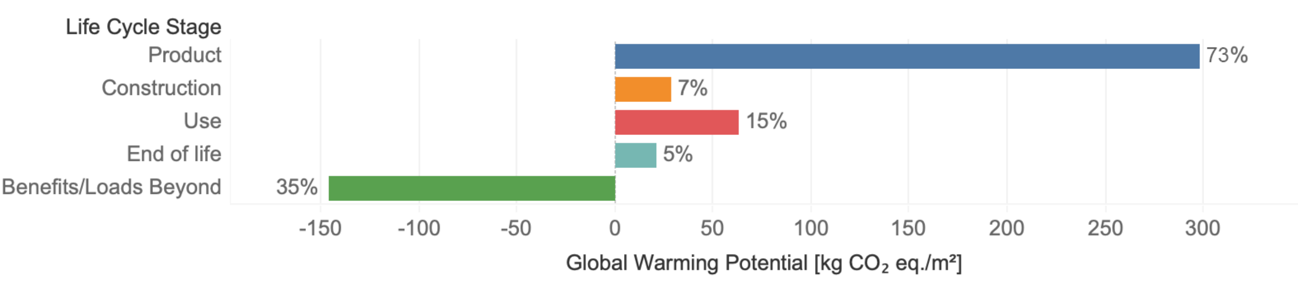

Figure 7 and Table 9: Assessment 2 results, breakdown by life cycle stage.

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 campus' 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 system 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. The CEC, like the BRDF, supports education and learning through tours, interactive signage, and displays.

Similar to the BRDF, this LEED Gold-certified building 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 slab-on-grade concrete foundation. The exterior walls are a mix of 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 and 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 insulation 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 project data sources from different stages of design development for the CEC, as well as three different embodied carbon assessment tools.

The five WBLCA from different stages of the CEC's design development all used Athena IE4B and were conducted:

- through the Athena IE4B assembly method with data drawn from architectural and structural BIM models done in Revit (Assessment 3);
- with material takeoff schedules exported directly from Revit from the same BIM models (Assessment 4);
- with material quantities and data from cost estimates created by project consultants at two stages of drawing development (Assessments 5 and 6); and
- with quantity takeoffs calculated by the research team from the architectural record drawings and the structural IFC drawings (Assessment 7).

Two additional assessments were conducted with the quantity takeoffs from the architectural record drawings and the structural IFC drawings using One Click LCA and EC3 (Assessments 8 and 9). These five assessments and results are detailed in the following sub-sections.

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


MAXIMUM LOAD=2500 KG
MAXIMUM LOAD=2500 KG

BUILDING: CEC

GROSS FLOOR AREA: 1,911 m²

PROJECT DATA SOURCE

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

BOM GENERATION METHOD

Athena IE4B assembly method

ASSESSMENT TOOL

Athena IE4B (Version 5.4.0101)

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

2.3.1 Assessment 3 – WBLCA using Assemblies from BIM model

Assessment 3 consists of a WBLCA, using the assembly method from the Athena IE4B tool according to the methodology detailed in Section 1.4. The assembly information (materials, dimensions, geometry, etc.) was sourced from an architectural BIM model created at 80% design development and a structural BIM model issued for permit. The object of assessment includes major building elements such as foundation (including steel reinforcement), 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 and stairs were excluded.

The research team entered the assemblies into the Athena IE4B tool, making substitutions for materials that do not exist in the tool's database. Unique elements in the CEC, such as custom structural members or products like rolling doors, required workarounds which included selection of similar materials, reasonable approximation of complex geometries, and addition of material quantities directly in the extra materials category.

Building Element (Modules A-C)	Global Warming Potential [Kg CO_2 eq/m²]	Impact Contribution [%]
Roofs	63.8	14%
Walls	256.9	56%
Floors	11.5	2%
Beams & Columns	32.6	7%
Foundations	97.9	21%
Total	462.7	100%

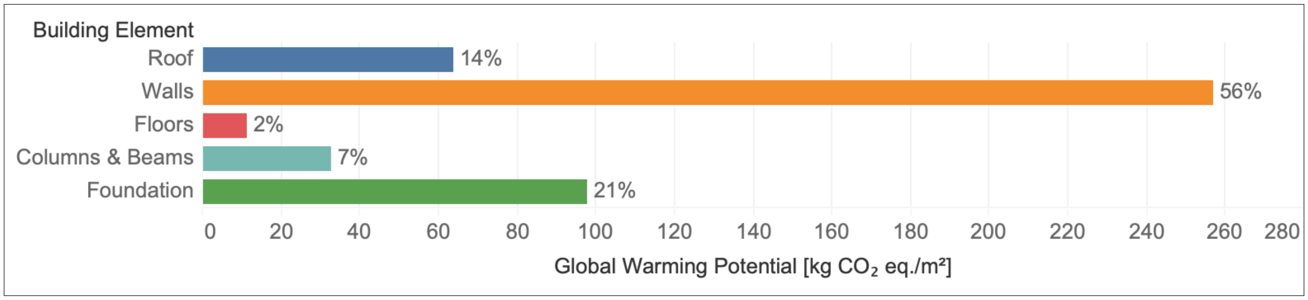

Figure 8 and Table 10: Assessment 3 results, breakdown by building element.

Assessment 3 – Results

Assessment 3 estimates that the CEC has a total GWP impact of 884,220 kg of CO_2 eq, or 462.7 kg of CO_2 eq per m^2. 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 method approach, the structural elements, such as CLT panels, are incorporated into floors, walls, and roof construction, according to the pre-set assemblies in Athena IE4B, although beam and columns are kept separate. When assigning assemblies, Athena IE4B automatically estimates the dimensions of columns and beams based on fixed span and bay sizes, and includes standard details such 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 benefits and loads beyond the system boundary are estimated to have the potential to offset up to 39% of the building's total impacts, partially due to the carbon sequestration potential of the mass timber, as well as the recycling potential of the steel and other metals.

Life Cycle Stage	Global Warming Potential [Kg CO_2 eq/m^2]	Impact Contribution [%]
Product (A1-A3)	295.0	64%
Construction process (A4-A5)	33.5	7%
Use (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%

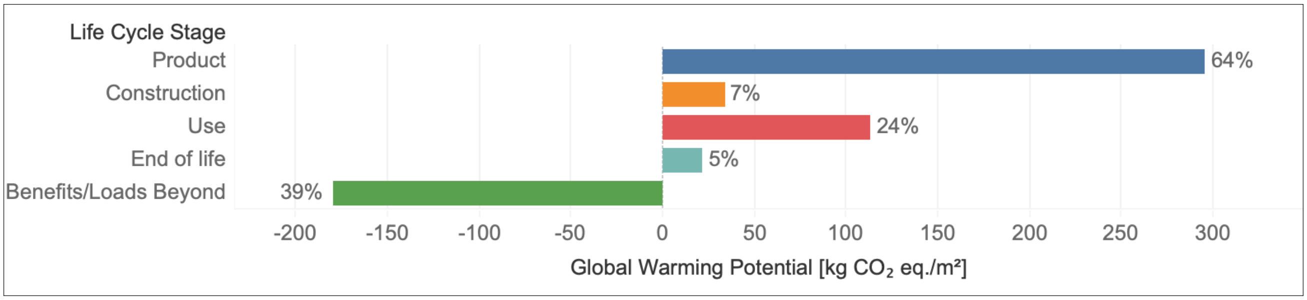

Figure 9 and Table 11: Assessment 3 results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA: 1,911 m^2

PROJECT **DATA SOURCE**

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

BOM GENERATION METHOD

Material Takeoff Schedule exported from Revit

ASSESSMENT TOOL

Athena IE4B (Version 5.4.0101)

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

2.3.2 Assessment 4 – WBLCA using BoM from BIM model

Assessment 4 consists of a WBLCA of the CEC using material quantities exported from the same architectural and structural BIM models used in Assessment 3 (created at about 80% design development and issued for permit). The BoM was developed using the Revit Material Takeoff Schedule feature, according to the methodology detailed in Section 1.4. Since the model was built using Autodesk Revit software, the material quantities and their associated properties were able to be exported directly from the model to Excel, then organized and complied for input into the Athena IE4B tool.

The object of assessment in Assessments 3 and 4 is similar since they share the same project data source: the BIM models. Assessment 4 includes foundation, floor construction, GLT beams and columns, steel beams, columns and trusses, roof construction and coverings, exterior wall construction and cladding. It also includes stair construction and interior load-bearing walls, which are not part of Assessment 3 (with the exception of one CLT interior wall). 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 and was not created for 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 IE4B tool selecting the materials from the tool's database. The mapped material list was relatively close to the exported BoM from Revit, but a few of the building's materials had to be replaced with materials with similar characteristics available in the database (e.g. zinc panels were entered as metal wall cladding).

Building Element (Modules A-C)	Global Warming Potential [Kg CO_2 eq/m²]	Impact Contribution [%]
Roofs	82.1	20%
Walls	213.0	53%
Floors	32.5	8%
Beams & Columns	22.6	6%
Foundations	51.3	13%
Total	401.5	100%

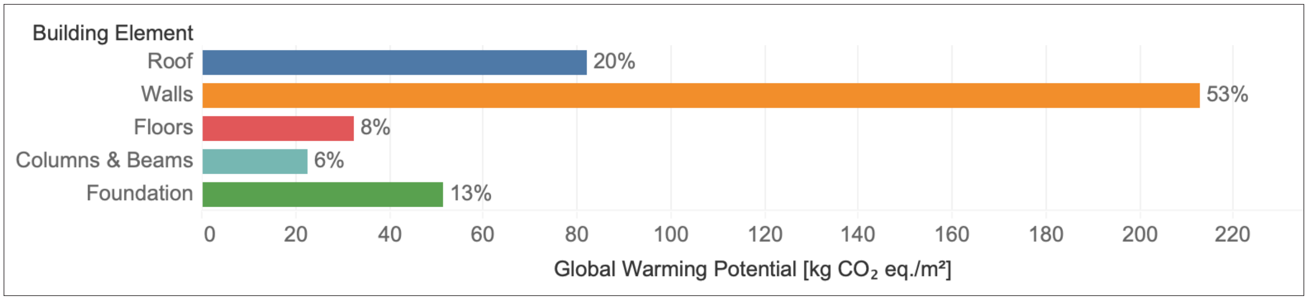

Figure 10 and Table 12: Assessment 4 results, breakdown by building element.

Assessment 4 – Results

Assessment 4 estimates that the CEC has a total GWP impact of 767,267 kg of CO_2 eq, or 401.5 kg of CO_2 eq per m^2. The largest contributors 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 method used to input the material quantities into the Athena IE4B tool (assembly method for Assessment 3 vs. BoM for Assessment 4). As mentioned before, the assembly method automatically estimates and includes standard details of assemblies, while the BoM assessment only included elements that were modeled in the BIM model, creating variations in the object of assessment and level of detail, 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 production stage.

Life Cycle Stage	Global Warming Potential [Kg CO_2 eq/m^2]	Impact Contribution [%]
Product (A1-A3)	238.2	59%
Construction process (A4-A5)	21.5	5%
Use (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%

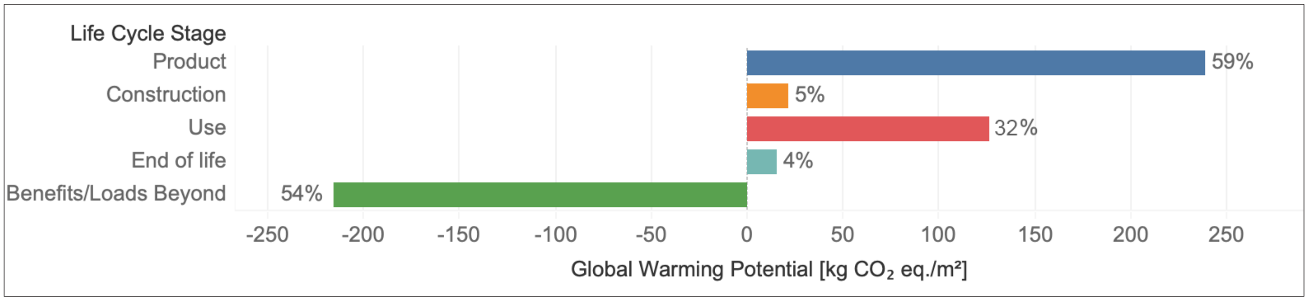

Figure 11 and Table 13: Assessment 4 results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA: 1,911 m²

PROJECT **DATA SOURCE**

Preliminary cost estimate - 50% design development drawings

(50% Drawings Estimate; September 6, 2013)

BOM GENERATION METHOD

Material quantities from cost estimate

ASSESSMENT TOOL

Athena IE4B (Version 5.4.0101)

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

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

Assessment 5 consists of a WBLCA using a BoM generated from a design development-phase cost estimate, calculated in Athena IE4B according to the methodology detailed in Section 1.4. 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 CO_2 eq/m²]	Impact Contribution [%]
Roofs	60.2	19%
Walls	144.4	45%
Floors	14.0	4%
Beams & Columns	17.6	5%
Foundations	85.3	27%
Total	321.5	100%

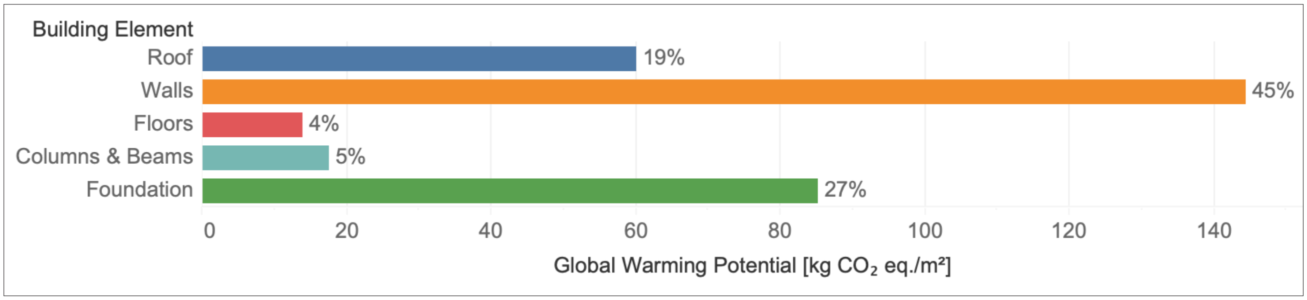

Figure 12 and Table 14: Assessment 5 results, breakdown by building element.

Assessment 5 – Results

Assessment 5 estimates that the CEC has a total GWP impact of 614,387 kg of CO_2 eq, or 321.5 kg of CO_2 eq per m^2. The GWP impacts calculated using the BoM data from this design-phase cost estimate are lower than the assessments based on the BIM models (Assessments 3 and 4). The overall material quantities were lower in the 50% cost estimate BoM than in the BIM models. This is possible 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 life cycle stages.

Life Cycle Stage	Global Warming Potential [Kg CO_2 eq/m^2]	Impact Contribution [%]
Product (A1-A3)	218.0	68%
Construction process (A4-A5)	21.5	7%
Use (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%

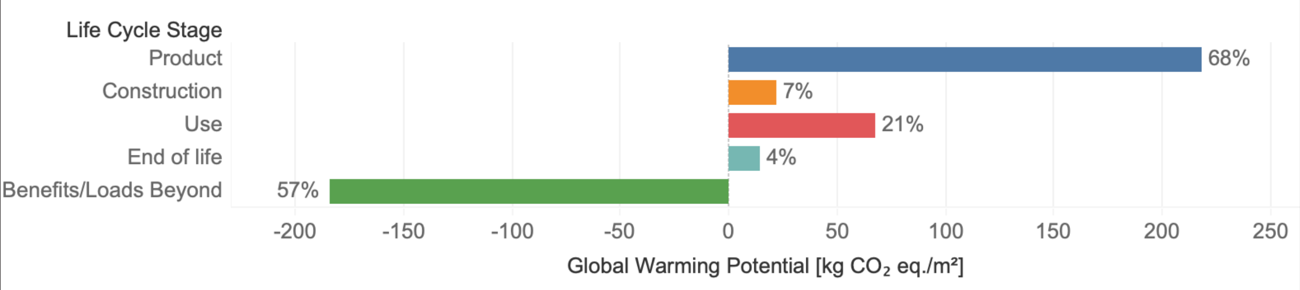

Figure 13 and Table 15: Assessment 5 results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA: 1,911 m²

PROJECT **DATA SOURCE**

Preliminary cost estimate - 85% design development drawings

(85% Costing Report; November 14, 2013, updated December 16, 2013)

BOM GENERATION METHOD

Material quantities from cost estimate

ASSESSMENT TOOL

Athena IE4B (Version 5.4.0101)

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

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

Similar to Assessment 5, Assessment 6 consists of a WBLCA using a BoM generated from a design development phase cost estimate and calculated on Athena IE4B according to the methodology detailed in Section 1.4. 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% design development 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 CO_2 eq/m²]	Impact Contribution [%]
Roofs	54.9	16%
Walls	175.3	50%
Floors	8.5	2%
Beams & Columns	39.7	11%
Foundations	72.7	21%
Total	351.1	100%

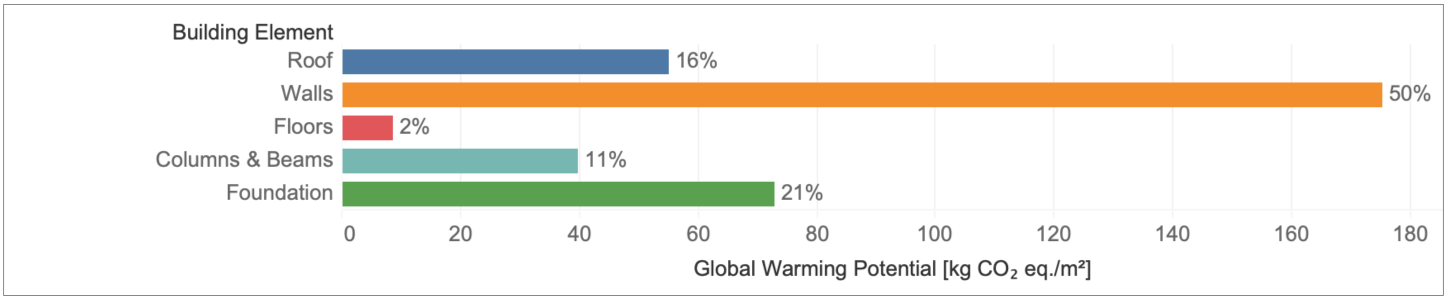

Figure 14 and Table 16: Assessment 6 results, breakdown by building element.

Assessment 6 – Results

Assessment 6 estimates that the CEC has a total GWP impact equivalent to 670,952 kg of CO_2 eq, or 351.1 kg of CO_2 eq per m^2. 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 evaluated at a 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 Assessment 5 due to an increase in quantity (or more accurate structural sizing) as the design developed. The quantities of materials categorized as beams and columns increased by 180% between the 50% and 85% cost estimates.

The product life cycle 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 life cycle stages.

Life Cycle Stage	Global Warming Potential [Kg CO_2 eq/m^2]	Impact Contribution [%]
Product (A1-A3)	246.6	70%
Construction process (A4-A5)	22.5	6%
Use (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%

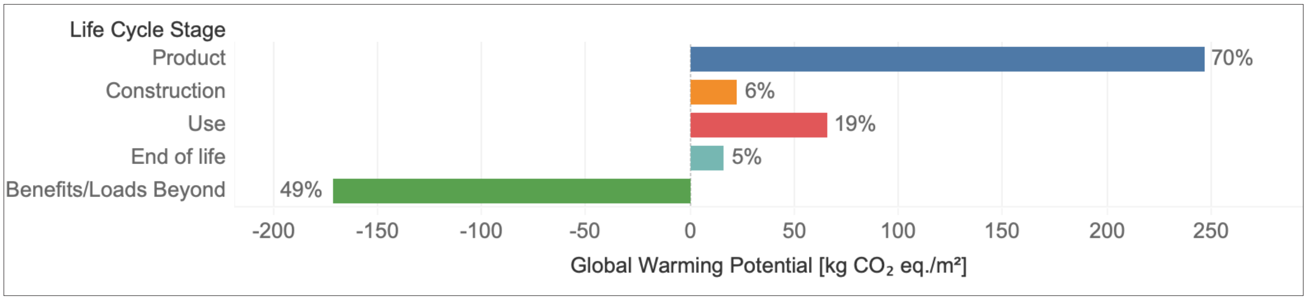

Figure 15 and Table 17: Assessment 6 results, breakdown by life cycle stage.

BUILDING: CEC

GROSS FLOOR AREA: 1,911 m^2

PROJECT **DATA SOURCE**

Record/IFC drawings (Architectural Record Drawings; June 29, 2016 /

Issued for Construction Structural Drawings; June 17, 2014)

BOM GENERATION METHOD

Quantity takeoffs from project drawings

ASSESSMENT TOOL

Athena IE4B (Version 5.4.0101)

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

2.3.5 Assessment 7 – WBLCA using BoM from IFC Drawings

Assessment 7 consists of a WBLCA calculated using Athena IE4B based on the methodology outlined in Section 1.4. For this assessment, the building's BoM was developed using material quantities from quantity takeoffs calculated by the research team from the project's architectural record drawings and structural IFC drawings. Beyond these, project specifications and shop drawings were also consulted to find and confirm materials. The research team used Bluebeam Revu to assist in quantifying the building's main elements from PDFs of the drawings. The BoM includes foundation, exterior walls (excluding membranes and minor finishes) and openings, roof construction (excluding coverings), floor construction, stairs, and beams and columns.

Building Element (Modules A-C)	Global Warming Potential [Kg CO_2 eq/m²]	Impact Contribution [%]
Roofs	32.2	8%
Walls	210.9	51%
Floors	53.9	13%
Beams & Columns	56.0	13%
Foundations	62.3	15%
Total	415.3	100%

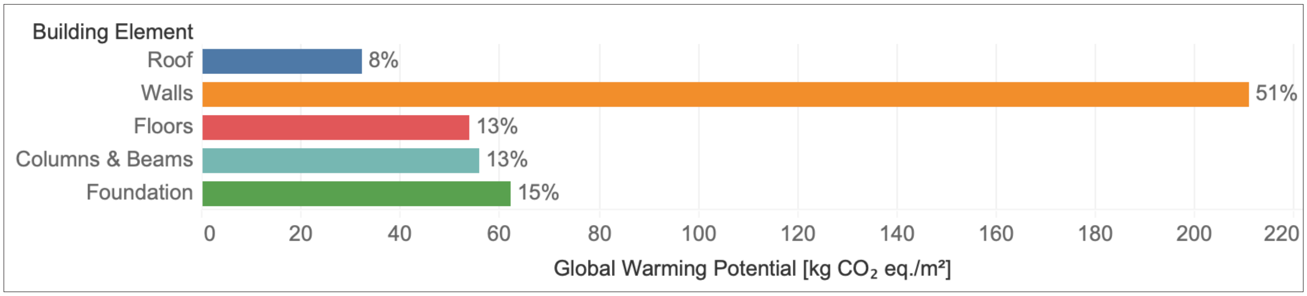

Figure 16 and Table 18: Assessment 7 results, breakdown by building element.

Assessment 7 – Results

Assessment 7 estimates that the CEC has a total GWP impact of 793,638 kg of CO_2 eq, or 415.3 kg of CO_2 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 roof remains 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 CO_2 eq/m²]	Impact Contribution [%]
Product (A1-A3)	275.4	66%
Construction process (A4-A5)	23.3	6%
Use (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%

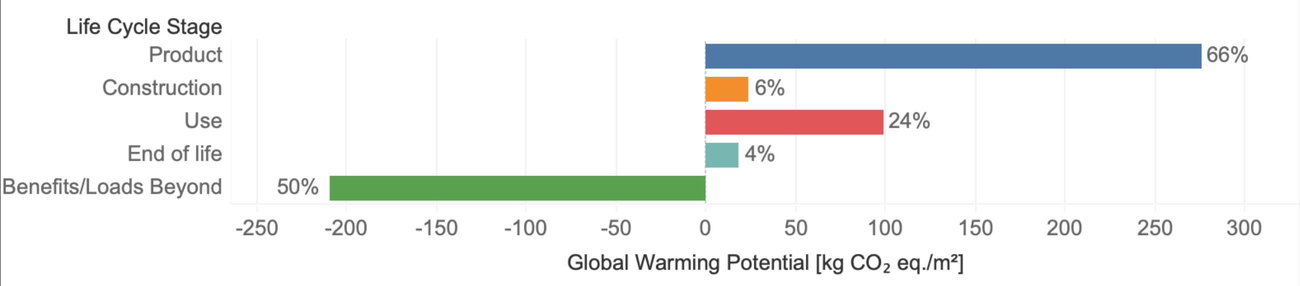

Figure 17 and Table 19: Assessment 7 results, breakdown by life cycle stage.

2.3.6 Assessment 8 – WBLCA using EC3

Assessment 8 consists of an embodied carbon assessment, using the same BoM generated for Assessment 7 based on quantity takeoffs from the record/IFC project drawings. In this case, the assessment was done using the Embodied Carbon in Construction Calculator (EC3). As described in Section 1, EC3 is a new online tool specifically intended to help users understand the embodied carbon impacts of material product. It draws on a database of industry-average and manufacturer-specific EPDs, and assesses impacts from the production life cycle stage (modules A1-A3). Since EC3 does not assess the environmental impacts of the construction, use, or end of life stages, it is not considered an LCA tool.

The BoM includes foundation, exterior walls (excluding membranes and minor finishes) and openings, roof construction (excluding coverings), floor construction, stairs, and beams and columns. The material information was translated into EPDs for the major building components, based on their availability in the EC3 database. The available EPDs did not cover all the materials in the building assemblies that are accounted for in the BoM, therefore materials such as the polyethylene moisture barrier, drainage plane membrane, and self-adhered membrane were excluded from the assessment, resulting in a smaller quantity of input data.

BUILDING: CEC

GROSS FLOOR AREA: 1,911 m^2

PROJECT **DATA SOURCE**

Record/IFC drawings (Architectural Record Drawings; June 29, 2016 /

Issued for Construction Structural Drawings; June 17, 2014)

BOM GENERATION METHOD

Quantity takeoffs from project drawings

ASSESSMENT TOOL

EC3 (Version v-22.1.1_b-1302)

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

Building Element (Modules A-C)	Global Warming Potential [Kg CO_2 eq/m²]	Impact Contribution [%]
Roofs	37.4	10%
Walls	112.2	31%
Floors	75.4	21%
Beams & Columns	73.3	20%
Foundations	66.5	18%
Total	364.8	100%

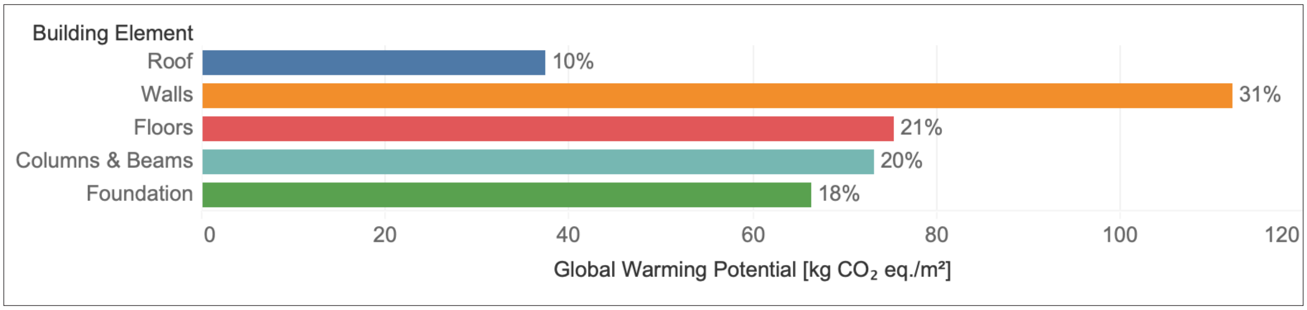

Figure 18 and Table 20: Assessment 8 average results in EC3, breakdown by building element.

Assessment 8 – Results

Assessment 8 estimates that the CEC has a total average GWP impact of 697,133 kg of CO_2 eq, or 364.8 kg of CO_2 eq per m². The EC3 tool reports GWP results as a range. To align with the other assessment, the impacts were also averaged. The average EC3 impact is significantly lower than the GWP impacts estimated by Athena IE4B in Assessment 7. However, the results are not directly comparable since the object of assessment, material selection, and system boundary vary when using different assessment tools.

In terms of building elements, the division of GWP impacts across building elements is more even in the EC3 calculation than the other embodied carbon assessment tools, possibly due to the restriction to the product stage and limits of matching EPDs. The exterior walls constitute the biggest impact, consistent with the other CEC assessments, but in this case are only 31% of the total. According to EC3, the second biggest contributor is floor construction (21%), followed by the foundation (18%), opposite that of Athena IE4B.

The EC3 approach assumes that not all EPDs have the same precision, that EPDs for a single product produced in a single factory are likely to be more precise than an industry-average EPD, and that EPDs of products with complex supply chains may have gaps of information. In EC3, an internal algorithm applies a proprietary uncertainty factor into the assessment and the results reported as a range: the 'conservative' result is the highest estimated impact, while the 'achievable' result is the lowest (Carbon Leadership Forum, 2019). As shown in this assessment, the range between the conservative and achievable can be quite large. For example, in the floors category the GWP impact in the conservative scenario is almost double than that of the achievable scenario, and in the roof category the conservative scenario is about one third higher than the achievable scenario.

Building Element (Modules A-C)	Conservative GWP [Kg CO_2 eq/m²]	Achievable GWP [Kg CO_2 eq/m²]
Roofs	42.6	32.2
Walls	123.6	100.9
Floors	100.2	50.7
Beams & Columns	96.1	50.4
Foundations	88.4	44.6
Total	450.9	278.8

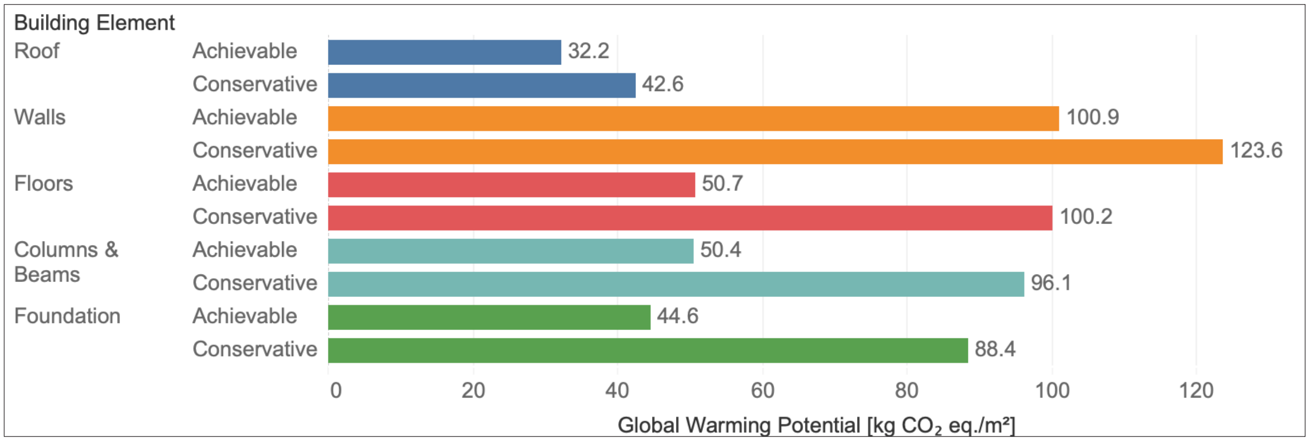

Figure 19 and Table 21: Assessment 8 conservative and achievable results in EC3, breakdown by building element.

BUILDING: CEC

GROSS FLOOR AREA: 1,911 m^2

PROJECT **DATA SOURCE**

Record/IFC drawings

(Architectural Record Drawings; June 29, 2016 /

Issued for Construction Structural Drawings; June 17, 2014)

BOM GENERATION METHOD

Quantity takeoffs from project drawings

ASSESSMENT TOOL

One Click LCA (Database Version 7.6)

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)

Transport to building site (A4)

Use (B1-B5)

End of Life (C1-C4)

BUILDING LIFETIME

Not applicable

2.3.7 Assessment 9 – WBLCA using One Click LCA

Similar to Assessment 7, Assessment 9 also consists of a WBLCA on the CEC using the same BoM based on quantity takeoffs from the record/IFC project drawings. In this case, the assessment was done using One Click LCA. As described in Section 1, One Click LCA is a web-based tool that relies on EPDs and 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 object of assessment for this WBLCA includes 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 IE4B in Assessment 7. Once the material sheet is imported the tool automatically maps the building materials to the available materials within the One Click LCA database. For materials to be successfully 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).

In this assessment, only material quantities and names were specified by the research team. This maintained consistent input with other assessments but the research team also did not have detailed project information to specify other input parameters, such as transportation distance between manufacturer and construction site. Therefore, certain user inputs typically required by One Click LCA in order to accurately calculate impacts across life cycle stages were either set to the tool's defaults or had to be excluded from the assessment.

Building Element (Modules A-C)	Global Warming Potential [Kg CO_2 eq/m²]	Impact Contribution [%]
Roofs	42.2	10%
Walls	119.3	27%
Floors	84.3	18%
Beams & Columns	123.8	28%
Foundations	73.4	17%
Total	443.0	100%

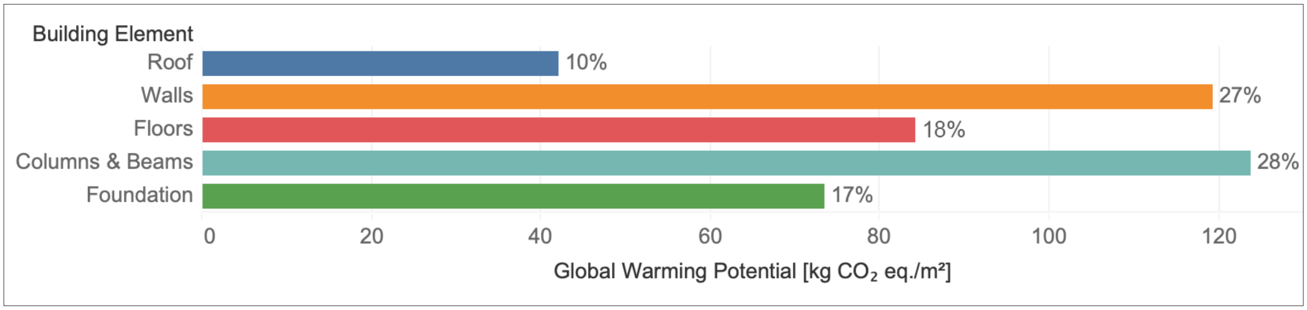

Figure 20 and Table 22: Assessment 9 results, breakdown by building element.

Assessment 9 – Results

Assessment 9 estimates that the CEC has a total GWP impact of 846,573 kg of CO_2 eq, or 443.0 kg of CO_2 eq per m². This impact is significantly higher than the total GWP impact estimated by Athena IE4B in Assessment 7. However, the results are not directly comparable since the object of assessment, material selection, and system boundary vary when using different assessment tools.

The distribution of GWP impacts across building elements is relatively even. In Assessment 9, two highest contributors are the beams and columns (28%) and the walls (27%), which together provide over half of the total GWP impacts. The floors and foundations are also close (18% and 17% respectively), while the roof is only 10%. The proportions are more similar to the results from EC3 than Athena IE4B, and are possibly due to similarity in the EPD approach or the focus on the product life cycle stage.

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

Life Cycle Stage	Global Warming Potential [Kg CO_2 eq/m²]	Impact Contribution [%]
Product (A1-A3)	385.6	87%
Transport to Building Site (A4)	29.0	7%
Use (B2-B5)	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

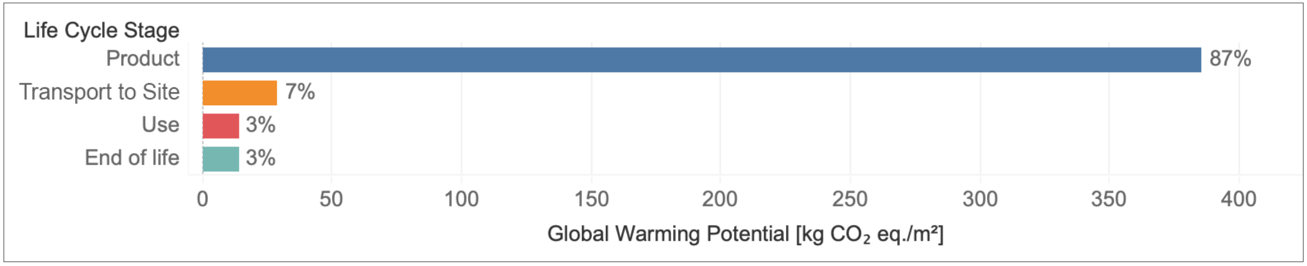

Figure 21 and Table 23: Assessment 9 results, breakdown by life cycle stage.

SECTION 3.0: ANALYSIS AND DISCUSSION

3.1 IMPACT OF DATA SOURCES ON MATERIAL QUANTITIES AND ASSESSMENT RESULTS

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 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 evolves as the building design is progressing. It is developed from the project documents, often from quantity takeoffs from project drawings or 3D BIM models. A preliminary BoM from the schematic design phase has less detail than a BoM created using construction documents, which provide the most accurate compilation of a building's materials. In addition, Athena IE4B, a WBLCA tool, can create an approximate BoM from data on the characteristics and geometry of the building assemblies using the assembly method.

The accuracy of a BoM influences the accuracy of a WBLCA. Collecting data from a BoM to use for benchmarking is more effective than WBLCA results due to built-in assumptions and differences between tools; BoMs also offer the flexibility to alter the WBLCA's scope to fit the desired analysis. 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 is to improve the use of embodied carbon assessments to inform policy by exploring the variations of WBLCA results based on different project data sources and BoM generation methods. The following analysis compares the assessments described in Section 2, focusing specifically on the differences in BoMs created from different project data sources, the differences in GWP results between the assessments, and the process and time required to create a BoM from different project data sources.

3.1.1 Variation of Input Method on Athena IE4B: 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 the Great Hall Wall) based on the same project data source but using two different methods of generating and inputting the list of materials into the Athena IE4B. The first list of materials was created in Excel by the research team based on quantity takeoffs calculated from the project drawings and imported into the tool. The second was created using the assembly method to input the materials and dimensions of the wall assemblies into the Athena IE4B tool, based on information from the same project drawings. The Athena IE4B tool then generated a list of materials based on the input information using its internal algorithms.

Kitchen Wall

The Longhouse Kitchen Wall is a conventional wall type (composed of wood stud framing, gypsum wall board, and cedar siding) and the materials therefore aligned closely with materials available in the Athena IE4B database for input via the assembly method. The list of materials created by the research team for the Kitchen Wall is based on the IFC drawings, and generally represents the structure as it was built. Therefore, the material selection and quantities generated by Athena IE4B through the assembly method should be relatively consistent with the materials and quantities generated through the quantity takeoffs, and both should represent a relatively accurate reflection of the actual wall in the building.

As illustrated in Table 24, the quantities of the significant materials, such as plywood, cedar siding, and gypsum board, are very similar between the two materials lists. The largest variation in significant material is the fiberglass insulation, which is only 7% higher in the assembly method. However, there are distinct differences between the two BoMs, particularly in omitted materials. Detailed materials, such as nails, screws, and paint, are generated by default in the Athena IE4B when entering the building assemblies through the assembly method. These detailed materials were not included in the quantity takeoffs because they were considered to be outside the object of assessment's boundaries, which focused on primary components and not fasteners or finishes. In addition, fasteners and finishes are difficult to accurately quantify and due to their small volume generally have minimal impacts when compared to major components (although paint is the exception here).

Great Hall Wall

Material	UoM	Material Quantity		% Difference
		Assembly Method	Quantity Takeoffs	
Regular Gypsum Board (5/8")	m^2	33.8	33.8	0.0%
Polyethylene (6 mil)	m^2	32.6	31.3	-3.8%
Cedar Wood Siding	m^2	135.1	135.1	0.0%
Fiberglass Insulation (R20)	m^2 (25mm)	174.7	162.6	-7.0%
Small Dimension Softwood Lumber	m^3	0.6	0.6	-3.2%
Softwood Plywood	m^2 (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	litres	72.7	-	-100%

Table 24. Variation of material quantities of the First Nations Longhouse kitchen wall, using the assembly method (baseline) and quantity takeoffs from project drawings.

The Great Hall Wall is a wood stud wall with cedar siding and felt acoustic finishes, and is less of a conventional construction then the Kitchen Wall. There are greater variations between the BoMs developed using Athena IE4B's assembly method and calculated using quantity takeoffs from project drawings, illustrated in Table 25. Again, some of the detailed materials, specifically fasteners and finishes, were not included in the quantity takeoffs from the project drawings but were added by default through the assembly method. All major material quantities are accounted for in both assessments. Generally, the quantities of the major material components, including fiberglass insulation, cedar siding, and organic felt, are close but slightly higher in the assembly method. Softwood lumber and plywood are lower in the assembly method, although the quantity of softwood lumber is quite small.

These two analyses illustrate the influence of the BoM generation method on variations in the resulting BoMs. Inaccuracies in tools' assumptions or human errors in quantity takeoffs can influence the GWP results, with minor or major effects. Understanding the development of both BoMs, as well as the extent of their impacts on the GWP impacts, relies on transparency throughout the process. These issues are further explored in the following analysis.

Material Name	**UoM**	**Material Quantity**		**% Difference**
		Assembly Method	Quantity Takeoffs	
Organic Felt (#15)	m²	562.1	539.2	-4.1%
Polyethylene (6 mil)	m²	104.6	96.5	-7.8%
Cedar Wood Siding	m²	433.9	416.2	-4.1%
Fiberglass Insulation (R20)	m² (25mm)	561.1	548.0	-2.3%
Small Dimension Softwood Lumber	m³	1.9	2.6	+42.6%
Softwood Plywood	m² (9mm)	137.7	176.8	+28.4%
Nails	tonnes	0.0	-	-100.0%
Screws, Nuts and Bolts	tonnes	0.0	-	-100.0%
Water Based Latex Paint	litres	233.4	-	-100.0%

Table 25. Variation of material quantities of the First Nations Longhouse Great Hall wall, using the assembly method (baseline) and quantity takeoffs from project drawings.

3.1.2 Variation of BoMs: Campus Energy Centre

As described in Section 2, the project team performed five WBLCAs on the CEC building using the Athena IE4B tool. The assessments were based on BoMs from four different project data sources (BIM architectural and structural models from 80% design development and issued for permit, cost estimates at 50% and 85% design development, and IFC/record drawings) and used four different generation methods.

The five WBLCAs with their project data source and BoM generation method are listed in Table 26. In all cases, except for Assessment 3, once the BoM was generated, it was organized and mapped to the selection of the materials in the Athena IE4B database by the research team on Excel, then imported into the Athena IE4B tool. For Assessment 3, the research team used Athena IE4B's assembly method to input material and geometry information, and the resulting BoM was then produced by the tool.

Assessment#	Project Data Source	BoM Generation Method
Assessment 3	BIM models	Assembly method - BoM generated by Athena IE4B based on the input of assembly characteristics sourced from the BIM model
Assessment 4	BIM models	BoM created by the research team based on material takeoff schedules exported directly from the Revit model software
Assessment 5	Professional cost estimate – 50% design development	BoM created by cost consultants based on design development documents
Assessment 6	Professional cost estimate – 85% design development	BoM created by cost consultants based on design development documents
Assessment 7	Record and IFC drawings	BoM created by the research team based on material quantity takeoffs from PDFs of project drawings

Table 26. Project data source and BoM generation methods for each CEC WBLCA using Athena IE4B.

The different project data sources and BoM generation methods led to variation in the types and quantities of materials included in the assessments' BoMs. A representative list of material categories and quantities calculated for the five Athena IE4B assessments is shown in Table 27, with all quantities displayed in units of mass (tonnes) for comparability purposes.

Materials and Building Elements	**Mass (tonnes)**				
	Assessment 3 BIM Model (Assembly Method)	**Assessment 4** BIM Model (BoM from Revit)	**Assessment 5** 50% Cost Estimate	**Assessment 6** 85% Cost Estimate	**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 27. Variations in material quantities among Assessments 3-7.

The assembly method, in Assessment 3, generated the list with the most variations in the material types because the Athena IE4B 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, extracted from the BIM model, relies on the geometries and specification of materials in the model, and generally includes major building components but not details like steel fasteners.

The BoMs in Assessments 5 and 6 include the material quantities estimated by the cost consultant using the same methodology but at different stages of design development. The BoM in Assessment 5 corresponds to 50% design cost estimate and therefore includes the least amount of materials. The project documents used for this BoM were the earliest in the design development process, focused on major components, and did not yet include quantities for elements like window frames and glass. The BoM in Assessment 6 corresponds to 85% design cost estimate and 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 quantification as part of a different building element in the BoM.

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

The variation in project data sources and BoM generation methods also led to variation in material quantities in different BoMs in each assessment. Table 28 illustrates these differences 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.

Materials and Building Elements	**Mass (tonnes)**				
	Assessment 3 BIM Model (Assembly Method)	**Assessment 4** BIM Model (BoM from Revit)	**Assessment 5** 50% Cost Estimate	**Assessment 6** 85% Cost Estimate	**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 28. Variation in material quantities between different BoMs of the CEC WBLCAs.

The BoM in Assessment 3, developed with the assembly method, has the highest quantities in six of the material type categories, and overall, its material quantities are generally higher than the other BoMs. The 'extra' categories are the highest by default, because those materials are not included in the scope for the other BoMs. The rest of the categories with higher materials quantities, however, likely reflect the built-in assumptions of the standard assemblies in Athena IE4B. The question then becomes, how close are the standard assemblies to the actual building? The CEC has a rather unique architectural and structural design, so the standards may not be that accurate. On the other hand, the assembly method may be picking up details not included in the scope of the other BoMs that together create a meaningful impact.

The BoM for Assessments 5 has the lowest quantities of materials, and was based on the earliest project documents with preliminary information on the components. Generally, the quantities of materials increase according to the design development progress. However, quantities slightly decrease between Assessments 6 and 7 (which are based on the 85% design development and construction documentation). This may be due to the increasing complexity of information throughout the design process followed by the refinement of the final design for construction documentation or to variations in BoM calculations methods between the cost consultant and the research team. In general, there are major variations in the quantities calculated for most of the materials from the different project data sources and different BoM generation 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.

In order to develop embodied carbon benchmarks, it is important to determine at what point in the project design is there sufficient information to develop an accurate WBLCA that reflects the real impacts of the building's material selection and quantities. Estimates taken too early in the design process may produce material quantities that are significantly higher or lower than the final design. Additionally, it is important to include the appropriate material categories as completely as possible. While higher quantities of materials generally lead to higher total GWP impact, certain materials have greater embodied emissions than others. For example, mass timber volumes are larger than metals like aluminum and steel, however metals typical have a greater rate of embodied carbon than wood. It is therefore not appropriate to limit the BoM to material categories with the largest volumes, and the design must be sufficiently developed to include at least a representative range of materials. This analysis begins to explore these issues, although no conclusions have been drawn from a single building project. In the following section the variability between the BoMs is examined in greater detail.

3.1.3 Variation of Project Data Sources and BoM Generation Methods: Campus Energy Centre

This section provides a more in-depth analysis of the material quantity variations across the BoM used in the different assessments: comparing the assembly method and quantity takeoffs from the BIM model developed at 80% design development (Table 29); comparing the two BoMs from the cost estimates (Table 30); and comparing the BoMs from the 85% design cost estimate and the IFC/record drawings (Table 31).

When examining the variation between 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 percent differences are high, but the actual material quantities are low, and therefore the difference will not have a significant impact on the total GWP. On the contrary, for materials with low percent differences but higher material quantities, even slight incremental differences in the percentages could significantly impact the material quantities and the total GWP.

BIM model assembly method and quantity takeoff variation

In this analysis, the variation of a representative selection of materials quantities from two different methods of compiling a BoM are explored: assembly method using Athena IE4B and direct export of material quantities from BIM software. These two assessments share the same project data source: the Revit architectural and structural models created at 80% design development and issued for permit, respectively. The percent difference is calculated using the assembly method as the baseline. The materials with lower quantities in Assessment 4 (shown in Table 29 as negative percentages in shades of red and orange) include the smaller wood members, major structural steel elements, aluminum in window frames and mullions, curtain wall and window glazing, structural concrete, insulation, and membranes, which range between 9% - 85% difference. The smaller wood members, which include wall framing and similar, have a large percent difference, but the total difference in the quantity of material for these elements is minor. Some materials that were excluded in the BIM model assessment were automatically included in the assembly method calculation.

The materials with the higher quantities in Assessment 4 (shown in Table 29 as positive percentages in shades of green) are the mass timber, secondary steel components, metal cladding, concrete blocks, and gypsum board, generally ranging 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 tonnes 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 project data source, the material quantities of each BoM vary substantially, which points to variation in the BoM generation methods. These variations include differences in the object of assessment, most notably with Assessment 4 including major interior structural walls; differences in the approach to quantifying materials, based on assembly method or the constructed BIM model; and differences in categorization of materials, especially small ones, again based on the assumptions within the Athena IE4B or the export from the BIM model.

Materials and Building Elements	Mass (tonnes)		
	Assessment 3 BIM Model (Assembly Method)	Assessment 4 BIM Model (BoM from Revit)	% 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 29. Variation of material quantities between assembly method and quantity takeoffs based on the project's BIM models.

Cost estimates' BoM variation

In this analysis, the variation of a representative selection of material quantities from two similar project data sources are compared: cost estimates at 50% and 85% design development. These BoMs were compiled by a professional cost consultant as part of the cost estimate based on design development documents. The consultant used the same method to create both BoMs and the same types of documents, but with differing level of detail and on different stages of the design development.

The percent difference was calculated with the BoM from Assessment 5 (50% design cost estimate) as the baseline. Similar to Table 29, where the BoM quantities from Assessment 6 (85% design cost estimate) are lower, the variation is shown as a negative percentage and highlighted in shades of orange; where it is higher, the variation is shown as a positive percentage and highlighted in shades of green.

The BoMs from these two different cost estimates 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 for the 85% design cost estimate, and about half the material quantities are higher. The only material from the first estimate that were later removed were barriers and membranes, which were likely incorporated into a different category by the consultant or removed due to changes in the design.

The elements that represent the most variation, both in terms of quantity and percent difference, are the mass timber and structural steel elements, metal cladding, insulation, and gypsum board. The quantity for smaller wood members has the highest increase in the 85% cost estimate (1,284%), but the quantity is much smaller than other structural elements. As these materials are major wall components, it makes sense that design decisions in the development phase would include refinement to the exterior walls. The increases in the mass timber and steel elements are possibly due to the development of the design informing more complexity and resolution in the structure. The quantity 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).

The BoMs developed for the cost estimates were created for that specific purpose, not to assess embodied carbon impacts. As indicated by the material omissions in the 50% cost estimates, the cost consultant based the BoM on information available and necessary for cost-based decision-making at that point in the design development process. From a WBLCA standpoint, they are incomplete. The omitted information, such as window frames and glazing could be filled in through other processes, such as the assembly method approach discussed in the previous analysis. That approach, however, would entail a certain amount of speculation, which depending on the omissions and the project, may not be accurate. This highlights the importance of a complete BoM, and indicates that BoMs from earlier in the design process, developed for other purposes, may not be an appropriate input for WBLCAs used to establish benchmarks and baselines.

Materials and Building Elements	**Mass (tonnes)**		
	Assessment 5 50% Cost Estimate	**Assessment 6** 85% Cost Estimate	**% 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 30. Variation of material quantities between the 50% and 85% cost estimates.

85% Cost Estimate and IFC drawing BoM variation

In this analysis, variations of a representative selection of materials from the BoM from the 85% design cost estimate (Assessment 6) is compared with the BoM developed by the research team based on the IFC and record drawings (Assessment 7). In terms of project data source, the IFC and record drawings (effectively 100% design development) contain more detail and information than the 85% design development drawings.

The percent differences were calculated with the BoM from Assessment 6 (85% design cost estimate) as the baseline. Where the BoM from Assessment 7 (IFC/record drawings) is lower, the variation is shown as a negative percentage and highlighted in shades of orange; when it is higher, the variation is shown as a positive percentage and highlighted in shades of green.

This analysis shows 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 takeoffs done by two different entities: a professional quantity surveyor and the research team.

Generally, the quantities of the materials in the BoM from Assessment 7 are lower than the BoM from Assessment 6. This could indicate refinement of the design (and associated materials and dimensions) as the drawings were finalized for construction, as well as variation in the quantity takeoffs between the cost consultant and the research team. As a professional, the cost consultant has a greater familiarity with the process and understanding of which details need to be included (although as discussed in the previous analysis, their purpose is to calculate costs, and the resulting analysis may include or emphasize different information than a BoM created for the explicit purpose of assessing environmental impacts). This is supported by the inclusion 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.

Materials and Building Elements	**Mass (tonnes)**		
	Assessment 6 85% Cost Estimate	**Assessment 7** Project Drawings	**% Difference**
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 31. Variation of material quantities between 85% cost estimate and quantity takeoffs from project drawings.

On the other hand, the most significant variation is the secondary steel components, which increased from 2.2 tonnes in the BoM in Assessment 6 to 33.6 tonnes 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 estimate, and included more components within this category, such as connections between mass timber structural elements as well as smaller steel elements. As a utility building, steel is a common material in the CEC.

Another relevant increase is in the sheet metal cladding, which almost doubles from the BoM from the 85% design cost estimate to the BoM from the IFC/record drawings. The sheet metal cladding 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 anomaly and points to a change in design that was later reversed, or possibly an omission or error in the documents or quantity takeoffs.

3.1.4 Variation of GWP for Different BoMs and Project Data Sources: Campus Energy Centre

As illustrated in the previous section, variations in the project data source and BoM generation methods will influence the quantities of materials in the BoM. This will in turn influence the results of the WBLCA.

The results from each assessment of the CEC using Athena IE4B were detailed in Section 2 (Assessments 3-7). In this section, the total GWP impacts from the WBLCAs are shown, broken down by building element (Figure 22) and life cycle stage (Figure 23). There is significant variation among the GWP impacts, driven by the differences in the BoMs, which in turn are due to differences in project data sources and BoM generation methods (see Section 3.1.2).

CEC GWP impacts breakdown by building element

The varying magnitudes of the total GWP impact correspond to the variations in materials quantities in the BoM, illustrating the direct connection between the BoM data and the WBLCA results. The assembly method WBLCA (Assessment 3) has the highest GWP impact of all the assessments, as well as the greatest quantities of materials and the most detailed list of included materials. However, the results are based on standardized versions of the assemblies and the tool's internal calculations, and may not directly match the actual materials in the building.

The variations through the other four assessments roughly follow the progression of the building design (cost estimate at 50% design development, cost estimate and BIM model at roughly 80-85% design development and IFC drawings at 100% design development). The proportion of impacts from the different building elements do not vary proportionally with the design progression overall: the impact of the roof decreases, the impact from floors and beams and columns increases, and the impact from the foundation and walls shows no trend. More information on material quantities and components were added to the drawings as the design was developed and as documents were prepared for construction, which should provide a more accurate reflection of the material types and quantities in the BoM.

The higher results from the BoM from the BIM model could potentially be due to the BoM generation method used. The material quantities were directly exported from Revit, therefore ensuring all materials included in the model were accounted for in the takeoffs. Interestingly, the total GWP impacts in the assessments based on the BIM model and IFC takeoffs are close, 401.5 and 415.3 kg of CO_2 eq/m^2 respectively, although this is likely a coincidence; the breakdown of the GWP by building elements is different between the two, which reflects differences in their respective BoMs.

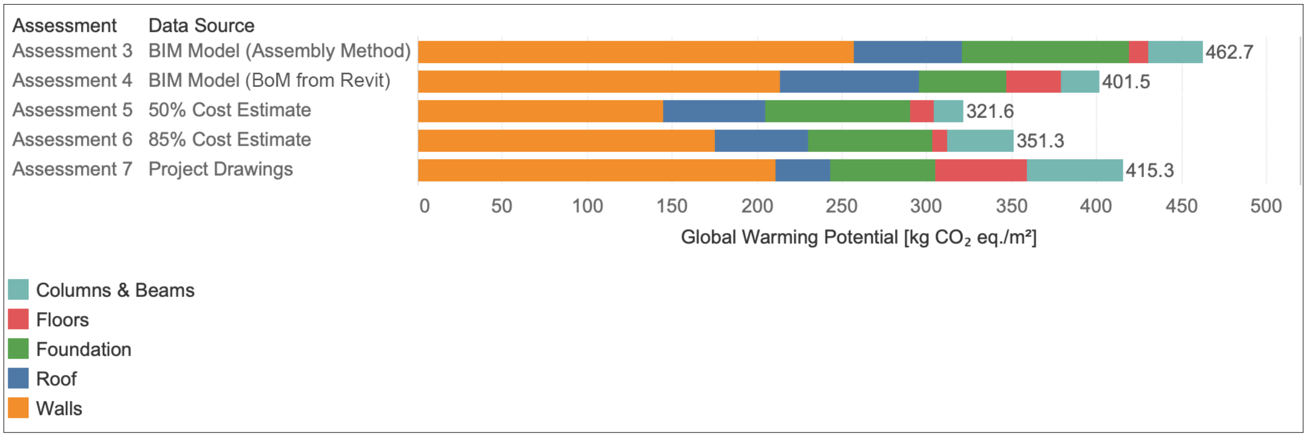

Figure 22: Variation of GWP impacts of the CEC WBLCAs calculated using Athena IE4B, breakdown by building element.

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, as shown in Figure 23. Although there is variation in the total GWP impacts, the distribution across building life cycle stages between the assessments is fairly consistent. This is partially influenced by the tool. All the assessments used the same WBLCA tool, Athena IE4B, which applied consistent assumptions for the impacts of different life cycle stages. Additionally, the decisions around mapping the BoM materials to the Athena IE4B database were made for one assessment and then applied to the others.

The largest contributing life cycle stage for all of the assessments, by far, is the production stage. Emissions from the manufacturing and production of materials are generally the highest for materials' life cycles. This is also where the data is the most robust. Construction activities, use and replacements, and end of life are highly influenced 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 assessments but also covers the longest period (100 years of the building's estimated life cycle) and includes renovations that 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 use stage (i.e. the useful life of the building).

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, such as wood and steel.

Athena IE4B 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 building elements) would be highly informative. The triangulation of major impacts from the life cycle stage, building elements, and individual materials would help to define the specific target area of high or low GWP impacts. This has been identified as future research in Section 4.

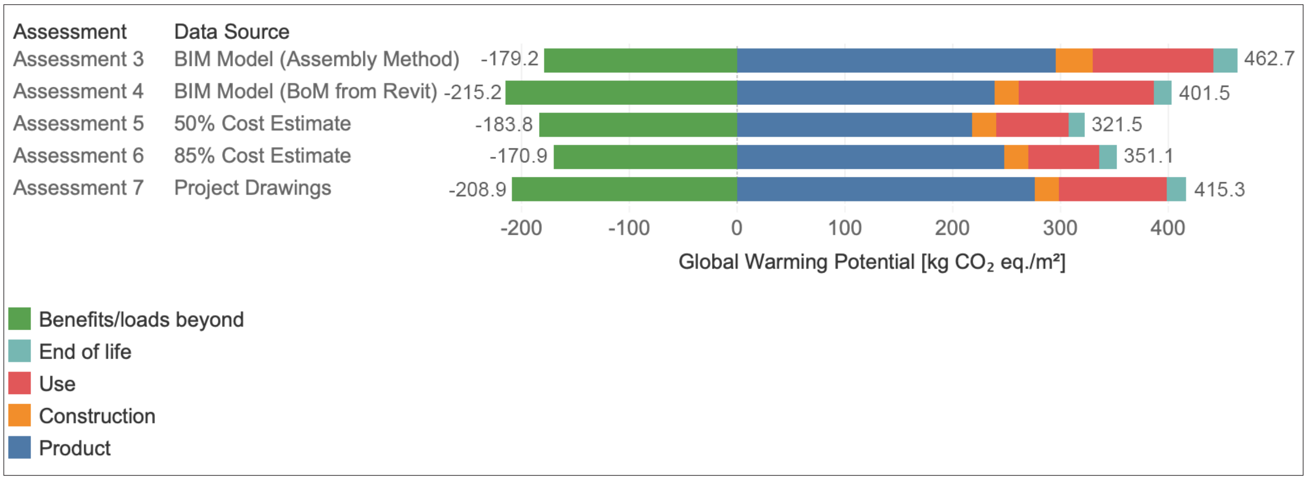

Figure 23: Variation of GWP impacts of the CEC WBLCAs calculated using Athena IE4B, breakdown by life cycle stage.

3.1.5 Variation of Work Time to Conduct WBLCAs from Different Project Data Sources: Campus Energy Centre

The research team tracked the work time spent on all of the assessments, from the project data collection, through development of the BoM and running the WBLCA. The purpose of this analysis was 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 it can be determined whether certain areas are worth investing more or less resources. In this section, the person-hours for all of the WBLCAs using Athena IE4B (Assessments 3-7) were categorized according to the four major tasks:

- Data extraction from source and processing.
- Material quantities calculations.
- Materials selection and mapping to the material selections in the embodied carbon assessment tool.
- Data input into the embodied carbon assessment tool to run the LCA.

The processing time by the Athena IE4B tool takes minutes and is not a noticeable part of the total time.

The graphs below show the breakdown of hours by task for the different assessments based on project 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 person-hours and GWP impacts by building elements for the IFC drawings-based assessment (Figure 26).

CEC person-hours per task across Athena IE4B 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 mainly because performing quantity takeoffs from project drawings is very time consuming, with data extraction and processing and materials quantities calculations taking 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.

It should be noted that the quantity takeoffs of the IFC and record drawings were done in-house by the research team, who are not professional quantity surveyors. The time spent on the quantity takeoffs includes learning curves for staff and students, as well as familiarization with the building 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 have still taken more time than the other assessments. The cost consultant's time to develop the BoMs used for the two cost estimates is not included in this comparison, as this information was not available. It would be valuable to get a better sense of the average time and costs associated with creating BoM in standard practice.

Material selection and mapping building-specific materials to the materials available in the Athena IE4B tool and recording assumptions were made during Assessment 7. The research team replicated those decisions for the other assessments (aside from the Assembly method), reducing the time required for material selection and mapping. If this task was repeated for each assessment the proportion of time would be greater. Relatedly, these assessments were all done within a few months of each other. Embodied carbon assessment tools' databases are continually being updated, and the material mapping must take into consideration new information on materials and products, in addition to the specifics of new building projects.

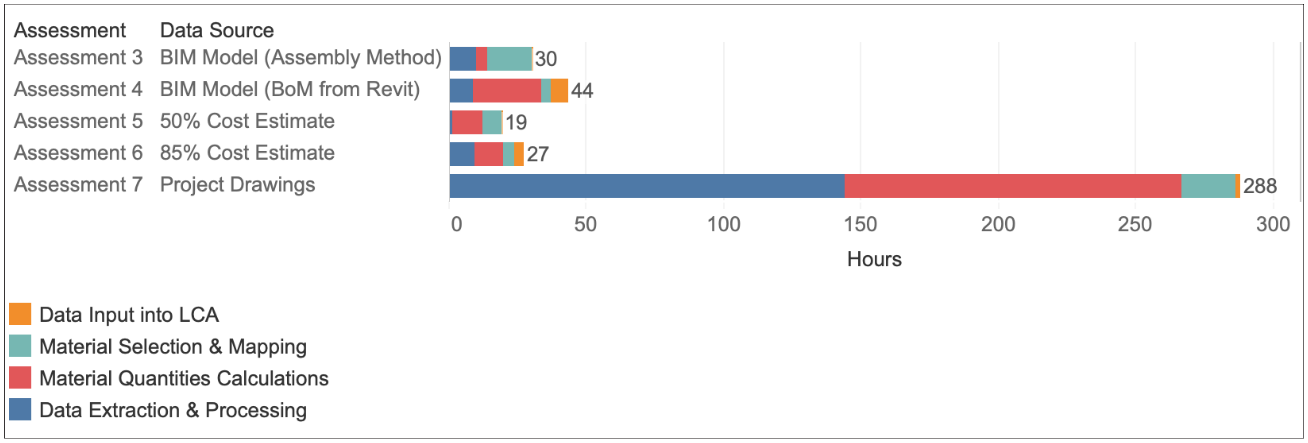

Figure 24: Variation of person-hours spent generating the BoMs and calculating the WBLCAs using Athena IE4B.

CEC person-hours per task by building element

Since Assessment 7, based on the IFC drawings, was the most time consuming, a more detailed breakdown of the total 288 hours to complete the WBLCA was compiled to understand which building elements required the most time and resources. Figure 25 shows the breakdown of the total person-hours by task, 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, with emphasis on the CEC's many wall types, which had to be matched to the plans and sections to determine wall type boundaries, dimensions, and material quantities for each wall layer.

Time allocations by task show that the data extraction and processing and material quantities calculations were the most time consuming, across all of the building elements. The time required to complete these tasks was also similar which indicates that, for the complex assemblies like walls and floors, it took just as much time to extract and process data from drawings as it did to calculate materials quantities. It is possible that if the research team were more familiar with the building's design or had more experience with quantity takeoffs, the total number of hours or their proportion by task may have shifted.

In comparison, material selection and mapping and input into the Athena IE4B tool required minimal time for all the elements. While LCA tools are considered to be user-friendly, the majority of the work required 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 embodied carbon assessment tools. Some suggestions are discussed in Section 4.

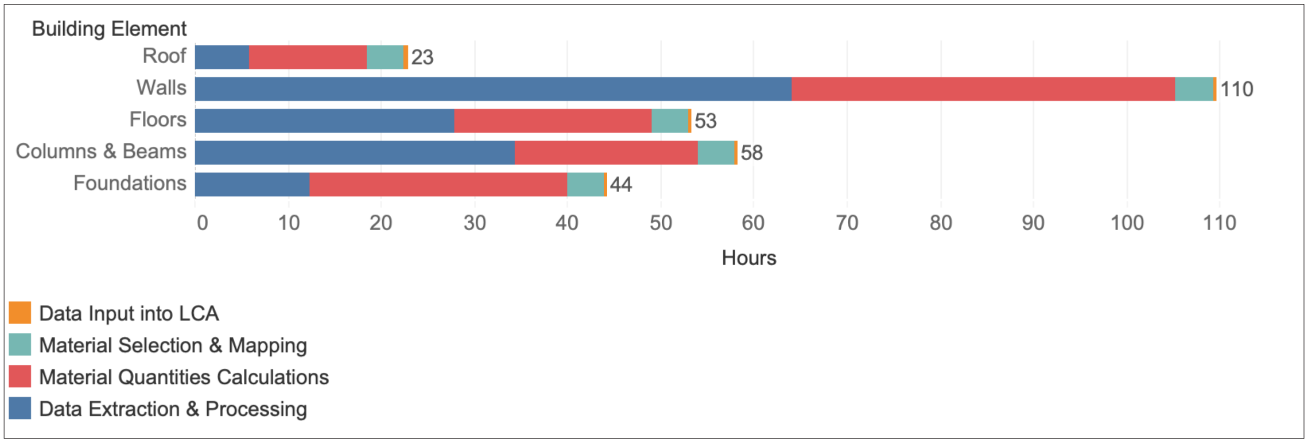

Figure 25: Variation of person-hours spent generating the BoM and calculating the WBLCA using Athena IE4B for Assessment 7, breakdown by building element.

Correlation of hours and GWP by building element

To further examine the relationship between time invested and WBLCA results, Figure 26 shows the relationship between the total time spent on each element (in grey, from Figure 25) and the total GWP impact for each element (in blue, from Figure 24). Generally, the time allocation coincides with the GWP impact, meaning 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 the most significant in terms of both time required and GWP impact, which reflects the complexity of assemblies and concentration of materials in that category. The floors category and the columns and beams category, on the other hand, took more time to calculate compared to their relative GWP impacts. These categories included some of the CEC's custom components, which used a hybrid of mass timber, steel, and concrete, and required more time for the research team to complete quantity takeoffs.

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

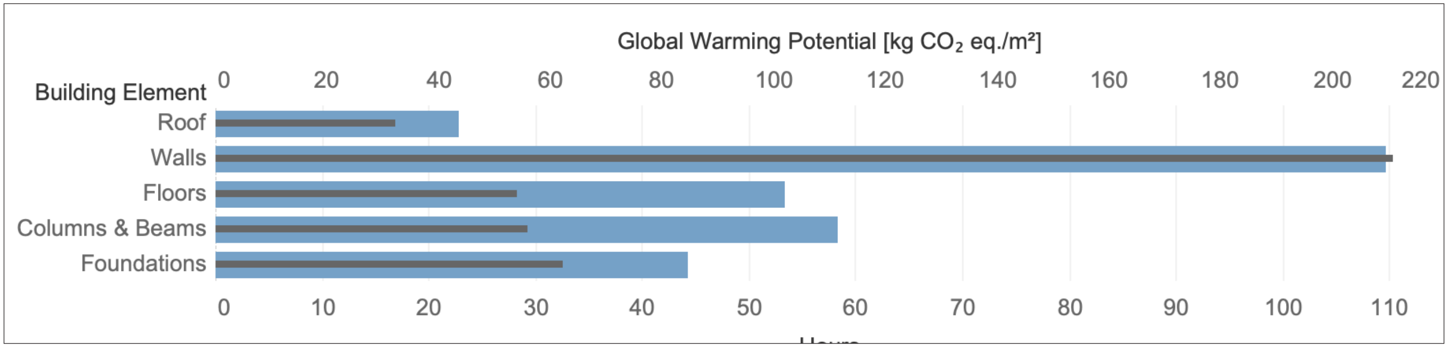

Figure 26: Correlation between person-hours spent generating the BoM and calculating the WBLCA (blue bar), and the GWP impacts (grey line) for Assessment 7, breakdown by building element.

3.2 IMPACT OF TOOLS ON ASSESSMENT RESULTS

Embodied carbon assessment tools are intended to streamline the process of calculating embodied carbon emissions from building design choices. Many of them are WBLCA tools that assess a number of environmental impacts, in addition to embodied carbon emissions or GWP. This Pilot includes assessments of the CEC, based on the same BoM, but using three different embodied carbon assessment tools: Athena IE4B, One Click LCA, and EC3. These are representative of a range of available tools being adopted by the building and construction industry.

This section explores the variations in scope, including system boundary and databases, and the influence on the total GWP impacts reported by each tool, broken down by life cycle stage and building element. Because of the differences in the assessments' scopes, the results are not comparable in themselves. The purpose of the analysis in this section is to examine different approaches, scope, classification, and databases used by the tools, in order to better inform considerations in policies and practices around embodied carbon emissions' benchmarking and performance targets.

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

3.2.1 Variation of System Boundary and Databases in Different Embodied Carbon Assessment Tools

The three embodied carbon assessment tools described in Section 1.4.4 vary in system boundary and include different life cycle stages. Broadly, these assessments multiply 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 information on the types of materials and quantities. The databases within the tools provide information on the environmental impacts. Table 32 illustrates the variations in system boundary for the assessment scope. The cell grouping in this table also represent the breakdown of the information given by the tool. Since this study only focuses on embodied carbon, the operational modules were excluded from the comparison.

Athena IE4B includes the life cycle stages broken down by module, as well as an estimation of external 'benefits beyond the building' (module D), such as carbon sequestration and reusability of materials. The system boundary is set by the user and individual modules can be removed. A list of the specific inclusions are provided as part of the WBLCA report. EC3 only includes the product life cycle stage in the system boundary and aggregates the modules (A1-A3) without providing any further breakdown. One Click LCA includes all the life cycle stages, but aggregates the modules per life cycle stage without further breakdown. 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. More detail on what is assessed in each module by tool can be found in Tables 3-5.

LIFE CYCLE STAGE	INFORMATION MODULE	ATHENA IE4B	ONE CLICK LCA	EC3
Product	A1 Raw material supply	X	X	X
	A2 Transport	X		
	A3 Manufacturing	X		
Construction	A4 Transport to building site	X	X	
	A5 Construction-installation process	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 Reuse, recovery, and recycling potential	X		

Table 32: Differences in embodied carbon assessment tool system boundaries for Assessments 7-9.

*Only four materials out of the whole BoM were assessed on modules B1-B5. One Click LCA requires additional user-given inputs to calculate the impacts on these modules, which the research team didn't specify when conducting Assessment 9.

The Athena IE4B proprietary LCI database is comprised of construction materials and energy resources from Canada and the United States. The source of this data is from Athena LCA studies, the Ecoinvent database, and the US LCI databases. Generally, industry average data is used, although manufacturer specific information is available for some products, but it also takes into consideration regional differences in things like fuel sources and transportation.

The One Click LCA database is composed of public and private, industry-average and manufacturer-specific EPDs, augmented by in-house research and data. More detailed information is available for European databases, while North America is still largely generic. Additional information can be entered by the user to inform life cycle stages beyond production, which are also limited by the information in the EPDs. In Assessment 9, only four materials from the whole BoM were included in the use life cycle stage (B1-B5).

The EC3 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, not Canada. EC3 assigns an embodied carbon range to each material to account for assumed uncertainty and variation in precision between different EPDs. The conservative GWP, which encompasses 80% of the relevant EPDs in the database, is the higher result and can be met by the most products currently available on the market. The achievable GWP, which encompasses 20% of the relevant EPDs in the database, is a lower impact and, while possible, can only be met if lower impact products are selected.

Recognizing the variation in system boundaries and types of databases between the tools is critical to understanding the variations in results. A WBLCA that includes all life cycle stages will have significantly higher results than an assessment only focused on the product stage, for example, but also provides a more complete representation of the building's environmental impacts over time. Similarly, while information on a number of key materials may be appropriate for making design decisions, a relatively comprehensive accounting of the embodied carbon emissions of a significant proportion of a building's materials is needed for use in benchmarking.

3.2.2 Variation of GWP Impacts of Embodied Carbon Assessment Tools by Building Elements: Campus Energy Centre

Given the variations in scope between the assessments within each tool, the results themselves are not comparable. The variations in this section are less concerned with the specific GWP impacts than 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 IE4B assessments in Section 3.1, the total GWP impacts by building element are broken down to highlight variations in assessments using different tools, as shown in Figure 27. For EC3, both the conservative and achievable results are used. The EC3 conservative scenario and One Click LCA results are the highest, and have a similar proportioned breakdown of impacts across the building elements (although One Click LCA includes impacts across more life cycle stages than EC3, which only includes the product stage). The EC3 achievable scenario is substantially lower since it includes only materials with low embodied emissions and only impacts from the production stage.

Selecting the materials in the embodied carbon assessment tool's databases that most closely represent the actual materials in the building is critical to ensuring the accuracy of the GWP results. Athena IE4B's materials database was the easiest to navigate for mapping materials, but the database is composed of material information that is not manufacturer-specific, so the results represent more of an industry average, which may be over or under the specific products used in the CEC. In contrast, EC3 and One Click LCA both have databases composed of information on both specific products and industry averages. However, if the actual product or manufacturer was not specified in the project documents or if the specific material was not available in the tools' database, the research team had to make assumptions when selecting the best alternative materials.

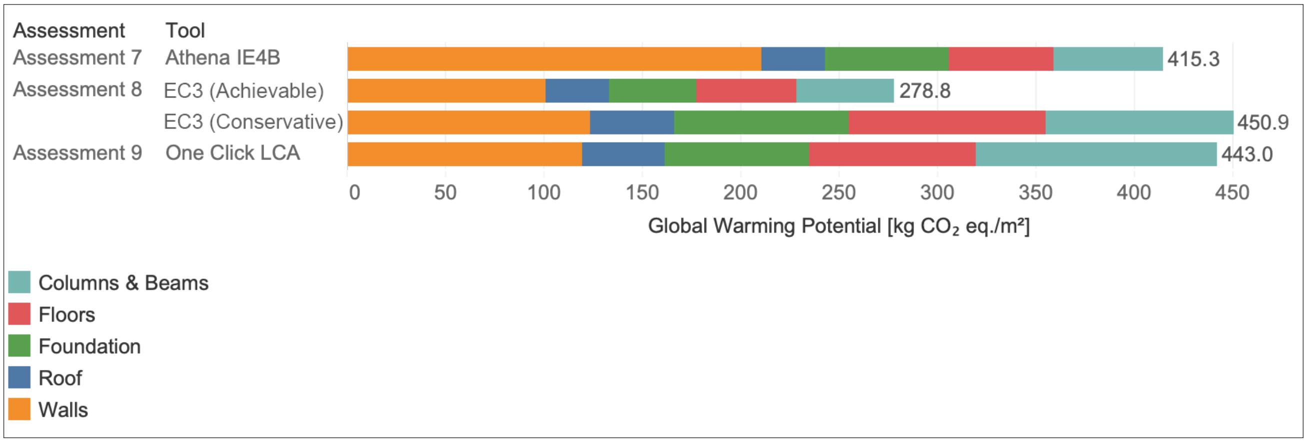

Figure 27: Variation of GWP impacts using different LCA tools, breakdown by building element.

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 their own classification system which categorizes assemblies such as columns and beams, floors, and walls. EC3 allows users to enter materials according to three different classification systems: UNIFORMAT II, MasterFormat, or a custom format. One Click LCA does not follow a standard building classification system. 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, more specific building element classification is offered. For example, within 'horizontal structures' the user can input: floor slabs, ceilings, roofing decks, beams, and roof. The research team attempted to maintain consistency in the classification of materials in the BoM between all three tools, but some adjustments were required.

3.2.3 Variation of GWP Impacts in Different Embodied Carbon Assessment Tools by Life Cycle Stages: Campus Energy Centre

As the three tools have different system boundaries, the variation illustrating the results breakdown by life cycle stage is highly informative. Since the project data source is the same for all the assessments, the variations are based on the tools themselves and their database, methodology, and assumptions. As with the building elements, both the achievable and conservative GWP impacts for EC3 are included.

Figure 28 highlights the differences in scope between the three embodied carbon assessment tools. While Athena IE4B 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 to note that the achievable impacts from EC3 are similar to the product stage impacts from Athena IE4B and the conservative impacts are similar to the product stage impacts from One Click LCA.

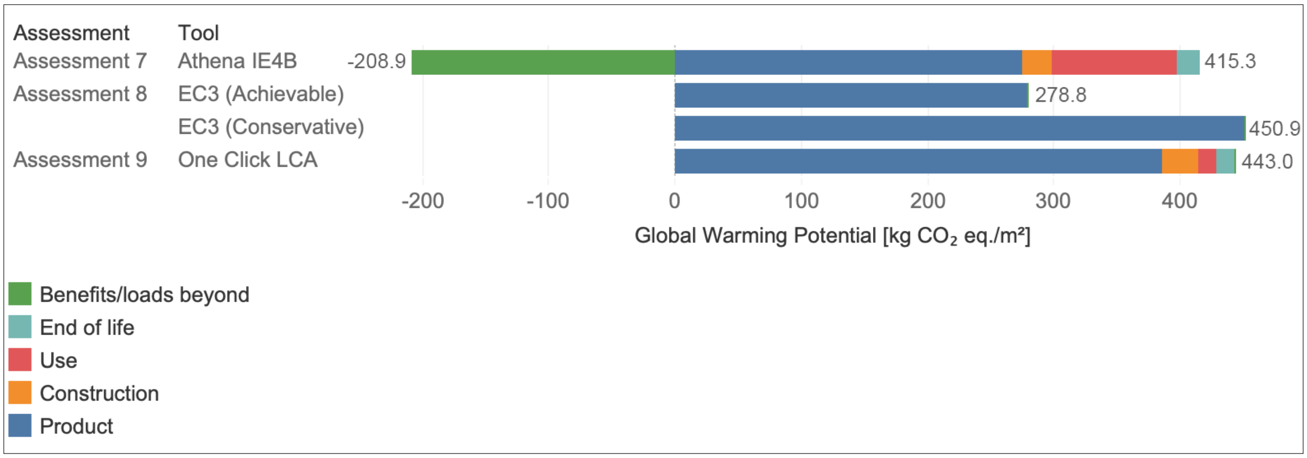

Figure 28: Variation of GWP impacts using different LCA tools, breakdown by life cycle stage.

Athena IE4B is the only tool that reports benefits and impacts beyond the building's life, as a way to account for some of the trade-offs in material selections. If materials can be reused or recycled, they lower another building's environmental impact and account for positive contributions from materials, such as carbon sequestration, which is valuable for offsetting GWP impacts. It should be recognized, however, that the data in this category is more speculative than the rest, both in how benefits are quantified and predictions in how materials may be used decades in the future.

3.3 IMPACT OF CONSULTANTS ON ASSESSMENT RESULTS

As part of the variation of the WBLCAs using different project 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. Three stages of design-phase LCAs were proposed:

- Stage 1: Comparison of the environmental impacts and life cycle costs of the structural element 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

Only Stage 1 and Stage 2 reports were obtained: 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 lifetime 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 lifetime is assumed to be 60 years.

In addition to the variation in scope, a review of the reports revealed variations in project 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 is dated approximately six months prior to the 50% design cost estimate that was used to create 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 IE4B tool. The Athena IE4B BoM is not the raw data from the project documents, but rather includes the consultant's assumptions and decisions 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 IE4B 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 project data sources, because they were created for specific purposes. Without a full understanding of the scope and data inputs, it is difficult to use the LCA results for anything beyond the original design decisions, and the studies have limited utility beyond that singular project end.

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 project data sources 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: CONCLUSIONS AND RECOMMENDATIONS

4.1 KEY FINDINGS AND CONCLUSIONS

In order to build a portfolio of existing buildings embodied carbon emissions that can be used to inform benchmarks and performance targets, the assessments need to be conducted with clear and standard parameters. Through the assessment and analysis describe in Section 2 and 3, five factors emerged that influence the variability:

- Project Data Sources: project documentation and models that contain information on the building design, components, and materials and their respective quantities.
- Object of Assessment: building components included in the assessment and the specific materials included in those components.
- BoM Generation Method: the protocols to quantify the building materials, categorize the information, and construct a BoM.
- System Boundary: the life cycle stages are included in the assessment and how that decision is made.
- Embodied Carbon Assessment Tool: the software tools, and associated materials databases, that calculate the environmental impacts of the materials selection and quantities.

LCA and embodied carbon assessments are complex, and these factors are interconnected. The sections below discuss the learnings from the assessment and analysis, divided into assessment inputs (e.g. project data sources, BoM, the tools materials database) and assessment outputs (e.g. usability and scope of results). The limitations of the research project are also addressed.

4.1.1 Assessment Inputs

The accuracy of the embodied carbon assessment results is dependent on the accuracy and completeness of the project data input into the assessment tool and the comprehensiveness of the tool's database and assumptions.

When assessing the embodied carbon emissions of building materials, one of the key data inputs is the quantities of all the materials, the BoM, within the object of assessment. Multiple steps are required to calculate the BoM and prepare the material quantities for input:

1. Collecting and organizing information from project data sources, recognizing that different data sources require different tasks and timelines (e.g. conducting quantity takeoffs from drawings either by hand or through an intermediate software, like Bluebeam Revu, vs. exporting material quantities from a BIM model via Excel spreadsheets).
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 to fill in gaps of information as needed).
3. Mapping the building materials to the material library within the tool's database and formatting the input for the specific tool (e.g. matching the formatting and naming conventions in the tool; replacing materials with a 'next best' option if the actual material is not available).

4. Inputting the materials information into the tool, either online or software. The imported BoM should be reviewed to ensure materials are identified and matched correctly. The process for inputting materials into the Athena IE4B tool using the assembly method varies from the process described here and requires different types of information.

Each of these steps require some level of decision-making and judgement by the user. Different decisions will create variations in the BoM and the data input, which will result in variations in the embodied carbon impacts. If the decisions and assumptions are not tracked, it is difficult to replicate the assessment, and validate the results.

Project data sources

The purpose of the assessment should drive the decision on what data sources to utilize, since there is substantial variation of GWP results between project data sources and the stage in the design process in which these were developed.

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 project 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. IFC or record drawings (or as-built models) 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 project data sources, since there are fewer components to include, however, it would not be an accurate reflection of the final construction and the resulting assessment would not accurately represent the environmental impacts of the actual building. However, data from earlier project phases can provide valuable insight if the objective of the assessment is to inform the building's design decisions and minimize its 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 project data sources would contain sufficient information on the major components, in a clear and easily accessible format.

Note that it's difficult to determine an appropriate level of design development from a study on a single project. This is an area for future research. Additionally, as the use of BIM models becomes more common throughout the industry, they may be a better project data source than drawings, since exporting materials is easier than quantity takeoffs. Currently, the use of BIM models is not consistent between projects and consultants.

BoM generation methods

The BoM is important for an accurate WBLCA – it needs to be carefully considered and can take significant time and resources to generate depending on the project data source and generation method.

A straightforward way to calculate a BoM is to do a quantity takeoff from the project drawings. Quantity takeoffs 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 takeoffs 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 project data source.

Quantity takeoffs are also very time-consuming. Although there are software tools that can assist, quantity takeoffs are still largely a manual process, which requires the 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 takeoffs are conducted, with room for human error and interpretations, and there are variations between different consultants.

When available, extracting a BoM from a BIM model is faster than a quantity takeoff from drawings, however, it is more dependent on the accuracy of the model. Modeling programs, like Autodesk Revit, allow users to directly export a material takeoff schedule created by the software from the information contained in the model. There is less subjectivity in this approach, but also less control and transparency for the user conducting the assessment. The internal software algorithms identify the size, shape, and properties of the modeled components and categorize them based on a set format. Any material or component not modeled is not included in the BoM, which can lead to omission of certain materials like rebar in concrete, or connection details in complex assemblies. Programs may also have trouble interpreting or counting certain materials, shapes, or items, especially if modelling 'best practices' are not applied. Some embodied carbon assessment tools can plug directly into the BIM model to calculate the building impacts, making the process easier but not necessarily more accurate.

Athena IE4B 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 relatively 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 WBLCA results. This input method is useful especially for the preliminary design of a standard building before precise quantities are known, 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, rebar, 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 embodied carbon assessment, a pre-existing BoM already created for the building project can be used. As mentioned above, BoMs are created for other purposes during the design process, such as cost estimates, and could be repurposed to be used on the assessment. 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. BoMs created for purposes other than an environmental impact assessment (or based on project documents or models created for other purposes) also may not include the same components or material information as one created purposefully for such an assessment.

Mapping the BoM to the embodied carbon assessment tool

The comprehensiveness of a tool's material database is as important as having a complete BoM, because this internal database dictates the accuracy in which the BoM can be mapped and assessed by the 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 tool. All tools rely on an internal database of information on different materials and products. These databases are frequently updated, but because buildings are unique entities and novel products, materials, and construction techniques are continually being developed within the industry, the specific materials from a building may or may not exist within the database.

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, to provide an accurate representation. The choices are largely subjective and require judgment based on familiarity with the building materials, as well as the tool. Even when materials are matched, variation can still occur. Therefore, there is a distinct and important difference between the building's actual BoM and the list of materials that is assessed by the tool. The level of variation between these two datasets will have an impact on the accuracy of the calculated GWP results calculated versus the real environmental impacts.

Many tools and databases rely on industry averages for many of their materials, which broaden the applicability, but may not be as accurate as the specific products. Additionally, many databases are grounded in certain markets (e.g. Europe or North America), which may limit the transferability of product information or regional variations in factors such as fuel sources and transportation options. With the growth of EPDs, some new embodied carbon assessment tools are building their databases around manufacturer or industry produced EPDs. In these cases, the tools use the information on material quantities from the BoM to select appropriate EPDs, as a way to quantify 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. EPDs can also create an inherent limit on the system boundary of the assessment, since they are focused on the production life cycle stage. Again, familiarity with both the building and the tool is required to map the BoM to the tool and establish appropriate parameters.

Input into the embodied carbon assessment tool

The tool's interface is important for ease of use but inputting the data into the tool requires the least time and resources compared to the rest of the assessment process.

Once the BoM information is mapped and formatted, it is entered into the 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 tools.

More than 98% of the time employed to calculate an embodied carbon assessment is spent preparing the data to be able to run it (i.e. categorizing the material quantities, converting units, and mapping the materials to the tool's materials library). The task of inputting the data into the tool and exporting the results is minimal and takes less than 2% of the total process time. Tool developers have focused on the robustness and user interactions of the tools, however, the substantial process described above must be completed before the data can be input into the tool, which is where the majority of the time and effort is required, along with subjective decisions and assumptions. This supports the need for more resources and guidelines for quantifying and translating material information from project documents to a clearly defined BoM, and from there, adapting the BoM for use in embodied carbon assessment tools.

4.1.2 Assessment Results

As shown in this Pilot, the results from an embodied carbon assessment can vary widely depending on the assessment inputs discussed above, as well as factors such as project data sources, scope of the assessment, and tools.

Assessment scope

The assessment scope should be aligned with its purpose (e.g. design decision-making, performance reporting, policy and benchmarking, etc.). For WBLCAs specifically, the scope should be comprehensive, which, in practice, is not always consistent and is dependent on data availability and the tool's database.

The scope of an embodied carbon assessment includes the object of assessment and the system boundary (i.e. the building components and the specific life cycle stages and modules included in the assessment). To effectively compare results, as is typically done for a design-phase assessment where the project team is deciding between multiple designs options, the scope of all assessments must be the same. However, in the case when the assessments are meant to inform design decisions, the building components and life cycle 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 assessment is intended to for use in setting policies around building performance, such as embodied carbon benchmarking and targets, assessing limited building elements and 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, also known as WBLCA. 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 reinforced 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 small 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 (e.g. gypsum board used as fireproofing could be considered part of the structure or an interior finish). In principle, the object of assessment should include major building components that contribute most of the embodied carbon emissions, with guidelines provided by policy around what should be included in those components and how materials should be classified. Greater standardization is needed here, as well as additional research to inform these decisions.

Establishing the system boundary (i.e. the life cycle stages to be assessed) can largely depend on the embodied carbon assessment tool, as different tools account for different life cycle stages. EC3, for example, only considers the product stage since the information is based on manufacturers EPDs, therefore falling outside of the definition of WBLCA. Some tools, like Athena IE4B, consider externalities, such as carbon sequestration, in a category referred to as ‘benefits and loads beyond the system boundary’ (module D), since it is a potentially positive contribution rather than a negative impact. Additionally, within tools, the life of the building can be set manually. Sixty years is a commonly used lifetime, especially in residential construction, but many larger buildings, especially institutional buildings, are intended to last longer than that. In principle, a complete WBLCA, however, should include all of the life cycle stages with a reasonable building lifetime for the typology and region.

Usability of assessment results

Assessment results vary widely depending on numerous factors such as scope, data source, BoM generation method, and tool, which means results between assessments have limited usefulness and are often not comparable.

Extracting results, which are given in different forms depending on the 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, and some only report results with a specific breakdown (by material, assembly, or life cycle stage). Additionally, while all tools incorporate some degree of built-in assumptions and limitations, there are varying levels of transparency into the information and how it influences the assessment results.

Depending on how the results of the assessment are meant to be used, their format and breakdown, as well as the 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 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 aggregations of other buildings as benchmarks, transparency is critical to ensure accuracy in the comparison. Part of the value of using a BoM-based approach is that it allows multiple points of comparison and analysis – of the building's actual BoM, of the inputs into the tool, and of the results. This would allow project teams to select buildings that are most similar to their own as references and help identify common areas of concern across certain typologies. Greater transparency can help identify the drivers of the embodied carbon emissions as well as effective solutions.

4.1.3 Research Limitations

Phase 1 of the Embodied Carbon Pilot, the basis for this report, was an exploratory project meant to improve understanding of the process of conducting embodied carbon assessments, illuminate gaps of information and other challenges, and start to identify potential solutions. It is the first phase in a multi-year project.

The research was limited by the availability of useful project data — originally the intent was to assess six different buildings, but securing BoMs and other project information for all of them was not attainable. The architect for the CEC, Dialog, provided a wealth of project documentation that allowed the research team to conduct different assessments on the same project.

Team capacity and timelines was another limiting factor. The time required to develop quantity takeoffs from the Longhouse and the CEC project drawings was significant, and more quantity takeoffs on other projects within the one-year timeline of the project could not be completed. Partly, this is because the team was composed of research project staff and student researchers, who had the opportunity to learn while conducting the current research project. While the research team focused more on understanding the gaps within the LCA process, a professional quantity surveyor would have been faster at conducting quantity takeoffs.

This Pilot is not intended to be a comprehensive review of all existing embodied carbon assessment tools. For example, a widely used WBLCA tool, Tally, was excluded from this phase because of functionality requirements and time limitations from the project. The selected tools represent some of the variations within the industry and allowed for an exploration of differences in input requirements and databases, as another factor in the range and influencer of variability in results. This study was not intended to as a methodical tool comparison.

The Phase 1 research has identified a number of factors in conducting embodied carbon assessments that should be addressed in the development of benchmarking practices and policies. While preliminary recommendations can be made based on the information in this report, future research in Phase 2 will test these findings and recommendations.

4.2 RECOMMENDATIONS AND FUTURE RESEARCH

Jurisdictions and organizations are beginning to develop policies around the use of embodied carbon assessments and WBLCA as a means to account for, and ultimately reduce, the embodied carbon emissions from their buildings. To more effectively use these types of tools, policies need to include more specific directions on how to conduct these assessments in order to standardize the data input and the results, and facilitate the use of these tools by project teams. The standardization, along with transparency of information and decisions, is critical to creating a collection of building projects and information that can be used to develop embodied carbon benchmarks and performance targets.

4.2.1 Policy and Guideline Recommendations

Based on the experiences and findings from Phase 1 of the Embodied Carbon Pilot, as described in this report, the research team has developed a preliminary set of recommendations for policymakers. These recommendations are divided into two categories: standardization of assessment parameters and submittals, and guidelines for assisting project teams in meeting these standards.

Standardization of assessment parameters and submittals:

The following recommendations are broad, as they are based on challenges identified within this research, and further research is necessary to develop optimal solutions or more detailed recommendations. More importantly, jurisdictions and organization will have their own priorities and contexts that should be considered in establishing standards, such as relevance of difference building typologies and average lifetimes or use of BIM models within projects. Specific standards should be established to serve the needs and purpose of the embodied carbon emissions policies.

When requiring embodied carbon assessments from project teams, policymakers should provide direction on:

- **Defined assessment scope**, including both the object of assessment (which building components are included) and system boundary (which life cycle stages are included) for new construction projects. Assessment scopes may vary by building typology, size or other major characteristics, programmatic needs, or performance requirements. Ideally a standard should be developed for major retrofits as well.
- **Selection of project data sources and BoM generation methods**, including information on the necessary level of design development, options for the types of project documents to use and means of calculating the building's BoM. Points one and two will help ensure that the material quantities in the resulting BoM are 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. Related to this, developing tools which can provide a breakdown of results by life cycle stage, building elements and materials, enables analysis of the intersection of impacts to help pinpoint major embodied carbon hotspots, which can then be targeted by policymakers and industry.

- **Expanding the submittal package** to include the quantities of the materials of the actual building in the BoM, as well as the input and results from the tools. Collecting more detailed packages of information builds a data set that can be analyzed and studied to identify more prescriptive or specific strategies for reducing embodied carbon emissions, and inform progressive performance targets.

Guidelines for assisting project teams:

Because the practice of calculating buildings' embodied carbon emissions is relatively new, greater guidance is needed to help practitioners navigate the assumptions and decisions that must be made throughout the process. The decisions made in developing the assessment inputs are critical to the value of the results, but as discussed in the previous sections, they are challenging and require trade-offs and familiarity with tools particularities. Guidelines should help project teams balance the detail and accuracy of the assessment with the work time required, and help ensure that submittals are consistent with the desired standards.

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

- The specific components that 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 the building lifetime, as well as guidance around the accounting of externalities like carbon sequestration.
- An appropriate level of design development at which to conduct an assessment 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 generation methods to use, or if this is established in policy or standards, guidance on how to develop a project data source and associated BoM to meet the requirements.
- How to make decisions when mapping the building's BoM to the material selection in a tool's 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 calculation processes, since these assumptions can meaningfully affect the results.
- The preferred and useful format of assessment results and supporting documentation that should be submitted to the jurisdiction or organization, to support the types of policy decisions being made.

This Pilot observed how multiple factors in the process of assessing embodied carbon emissions can affect the resulting impacts, which can vary widely. Therefore, clear guidance from policy and subject matter experts can help project teams address these factors and develop a structured, data-driven approach to embodied emissions benchmarks and targets for buildings.

4.2.2 Future Research

The first phase of the Embodied Carbon Pilot, described in Sections 1-3, was exploratory by nature. Building on experiences with WBLCAs conducted on two UBC student residences, Brock Commons Tallwood House and Ponderosa Commons Cedar House, the Pilot sought to develop a more detailed understanding of the variations within LCAs and embodied carbon assessments as a practice and the factors that influence the results. Nine assessments were conducted on three buildings, using different project data sources, BoM generation methods, and embodied carbon assessment tools, and comparing the data inputs, results, and work time for the assessments.

Phase 1 provided valuable insight into how the factors that affect the inputs, process, and results of embodied carbon assessments in a way that can be used to inform policy, as opposed to design decisions within a single project. Phase 2 will further advance this work by starting to develop sample standards and guidelines as described above and testing them by conducting embodied carbon assessment on multiple building projects of similar typology, mid-rise multi-unit residential buildings.

In Phase 2, the research will focus on the practices that inform the development of BoMs, including trade-offs between the level of detail from the project data source and ease of developing a BoM; strategies for including materials and components in the object of assessment, addressing hotspots and major contributors to embodied carbon emissions; as well as the interpretation of building BoM into inputs for embodied carbon assessment tools. By studying multiple buildings of the same type, is it possible to continue exploring the intersection of embodied carbon impacts from life cycle stages, building elements, and materials choices, and investigate processes and tools that can be effectively used for establishing benchmarks and, eventually, performance targets for embodied carbon in buildings.

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