UBC EMBODIED CARBON PILOT

Phase II - Final report

THE UNIVERSITY OF BRITISH COLUMBIA
sustainability

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The report describes pilot whole building life cycle assessments conducted on BC buildings and analysis of the results for the Embodied Carbon Pilot, between April 2020 and March 2021.

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LIST OF ABBREVIATIONS

Athena IE4B | Athena Impact Estimator for Buildings

BIM | Building information model

BoM | Bill of materials

CO_2 | Carbon dioxide

EPD | Environmental product declaration

GFA | Gross floor area

GHG | Greenhouse gas

GWP | Global warming potential

IFC | Issued for construction

IFT | Issued for tender

ISO | International Organization of Standardization

kg CO_2 eq | Kilograms of carbon dioxide equivalent

LCA | Life cycle assessment

LCI | Life cycle inventory (analysis)

LCIA | Life cycle impact assessment

LOD | Level of development

Pilot | Embodied carbon pilot

UBC | University of British Columbia

UoM | Unit of measure

WBLCA | Whole-building life cycle assessment

GLOSSARY OF TERMS

Bill of Materials | the list of product flow quantities included in building model scope that make up the physical building (National Research Council Canada, 2021)

Building Information Model | a digital representation of physical and functional characteristics of a facility; as such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward (National BIM Standard - United States, 2015)

Embodied Carbon Emissions | the total GHG emissions, measured in equivalence to CO_2, associated with materials and products in a built asset from some or all of the building life cycle stages, but excluding operational energy and water uses

Environmental Impact Category | class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (ISO 14040:2006)

Environmental Product Declaration | a third-party verified report providing quantified environmental data (impacts) using predetermined parameters and, where relevant, additional environmental information (ISO 21930:2017)

Greenhouse Gases | any of various gaseous compounds (such as carbon dioxide or methane) that absorb infrared radiation, trap heat in the atmosphere and contribute to the greenhouse effect (Merriam-Webster Dictionary, 2021)

Level of Development | a reference used to specify and articulate the content and reliability of Building Information Models at various stages in the design and construction process (Level of Development Specification, Associated General Contractors of America, 2019)

Life Cycle Assessment | compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product throughout its life cycle (ISO 14040:2006)

Life Cycle Inventory Analysis | phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO14040:2006)

Life Cycle Stages | consecutive and interlinked stages of a product from raw material acquisition or generation of natural resources to the final disposal (ISO 14040:2006)

Object of Assessment | the building, including its foundations and external works within the curtilage of the building's site, over its life cycle (EN 15978:2011)

Quantity Takeoff | the detailed measurement process of quantifying a building's materials and components from project documentation

Reference Study Period | the period over which the time-dependent characteristics of the object of assessment are analyzed (EN 15978:2011)

System Boundary | the interface in the assessment between a building and its surroundings or other product systems (EN 15978:2011)

Whole Building Life Cycle Assessment | life cycle assessment applied to a building-related functional equivalent —a whole building, or part of a building (National Research Council Canada, 2021)

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1 INTRODUCTION

1.1 Life cycle assessment to estimate embodied carbon

The building sector is a significant contributor to the planet's rising levels of greenhouse gases (GHGs) and is responsible for 39% of all global GHG emissions. Of this 39%, operational emissions account for approximately 28%, while the manufacture and construction of buildings account for 11%, as illustrated in Figure 1 (UN Environment and International Energy Agency, 2017). The building industry has focused on reducing operational emissions by decreasing buildings' energy consumption through advancements in technology, design, and regulations. However, with this reduction of operational emissions, embodied emissions from building material choices are becoming proportionally more significant. Embodied emissions are the GHG emissions generated from the resource extraction, manufacturing, transportation, construction, use, recycling and disposal of the materials and products in a building. Embodied emissions, also known as carbon emissions, are named after carbon dioxide (CO_2) but refer to numerous GHGs that retain thermal energy when emitted into the atmosphere. Each of these gas compounds contributes differently to global warming and are simplified into a carbon dioxide equivalent generally reported in kilograms of carbon dioxide equivalent (kg CO_2 eq.).

Embodied carbon emissions for a product or a whole building can be calculated with life cycle assessment (LCA), an analytical technique for quantifying the potential environmental impacts associated with a product's manufacturing, transportation, use, and end-of-life disposition. Carbon emissions are only one of the environmental impacts that LCA is capable of measuring, and is indicated by the global warming potential (GWP) impact category.

LCA can be applied to any type of product, including buildings as a whole or their individual components. When the entire building project is considered holistically in an LCA exercise – as opposed to LCA applied only to parts of the building – it can be referred to as whole-building LCA (WBLCA). Assessing the embodied carbon of a whole building requires access to carbon emissions data for all the materials and processes involved in a building over its life cycle. There is a range of software tools and environmental impact databases that provide this information for design professionals and LCA consultants to use in conducting WBLCA.

A WBLCA can be conducted at different points throughout the process of design, to inform sustainable design decisions, demonstrate adherence to performance targets, and establish benchmarks. For example, during design, WBLCA allows practitioners to compare the impacts of different material and design choices. Practitioners can also conduct WBLCA on completed buildings, during or after construction, to document and report the carbon emissions and other environmental impacts of the whole building. This reporting can be used to comply with regulations or certifications or to demonstrate the achievement of certain performance targets.

Collecting embodied emissions data from multiple buildings (of similar typology, construction type, geographical region, etc.) can help policy-makers or building owners establish benchmarks or baselines for performance targets of future construction projects. However,

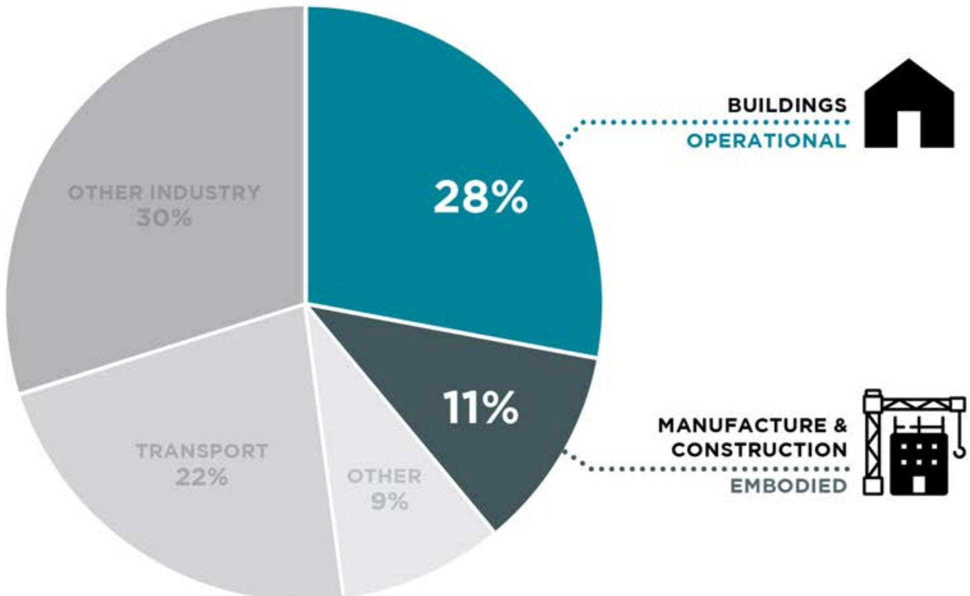


Figure 1: Share of global energy-related CO_2 emissions (adapted from Global Status Report, 2017)

variations in assessment scope between different LCA tools, approaches, data sources and material quantity calculation methods, mean LCA results are not usually comparable or consistent between building projects. These variations limit the utility of the results in developing policy, standards or regulations.

LCAs are becoming more common in the building industry, used in both design and policy decisions. However, while the number of assessment tools has increased, and significant work has been done to expand and improve tools' back-end databases and front-end user functionality, the process of data preparation prior to input into the LCA tool remains largely unstructured. To conduct an LCA, a practitioner must first create a list of the different materials and quantities in the building– a bill of materials (BoM) – which can then be input into the LCA tool to assess the environmental impacts. There are a number of decisions and assumptions inherent in the creation of a BoM, which contribute to the variations in LCA results. Greater guidance and standardization are needed to ensure that the process of developing BoM information for LCAs is consistent across building projects so that it can be used to establish accurate embodied carbon emissions benchmarks and performance targets.

1.2 Objective

Developing a comprehensive system for the collection, organization, and manipulation of building and materials data is necessary to support the creation of consistent BoMs to advance the use of LCAs in policy and practice. This section aims to address the need for more detailed guidance for BoM-based WBLCAs by describing a set of procedures for establishing the parameters of the LCA and generating a building's BoM for input into an LCA tool. The methodology starts by describing the assessment parameters that practitioners should set at the beginning of the data preparation process, then outlines a data preparation methodology as the first step towards a more standardized approach. It also highlights the need for practitioners to document the assumptions and decisions made throughout the BoM and LCA processes.

While primarily focused on embodied carbon emissions and WBLCAs, this methodology describes an approach to compiling data and creating a list of material quantities for input into LCA tools that could be applied to the assessment of other environmental impacts. Understanding the factors that influence this data collection and LCA input process is essential to identify potential inconsistencies and improve future guidelines. This section provides a descriptive approach, rather than a prescriptive one, to the data preparation process to promote discussion around the need for further development in this field.

1.3 Methodology Background

The methodology described in this section is based on the process developed in Phase 1 of the Embodied Carbon Pilot (Pilot), conducted by the University of British Columbia Sustainability Initiative in 2019-2020. Learnings from the Pilot are informing policy development and guidelines for embodied carbon assessment, benchmarks, and eventually, performance targets of buildings within and outside the UBC campus.

In Phase 1 of the Pilot, the research team conducted nine embodied carbon assessments with a variety of different parameters: type of building, project data source, design stage, carbon assessment tool, and data input method. Through the various assessments, the research team developed a standardized approach to collecting project information and generating BoMs for input into the assessment tools, while also identifying several research and policy gaps. This methodology is being tested and refined through Phase 2 of the Pilot. While the methodology is focused on the assessment of embodied carbon emissions, it can be broadly applied to other environmental impact categories as well.

1.4 Methodology Framework

Conducting an LCA involves multiple steps which can be categorized in four phases, as set out by the International Organization of Standardization (ISO) in the standards ISO 14040 (Environmental management – Life cycle assessment – Principles and Frameworks) and ISO 14044 (Environmental management – Life cycle assessment – Requirements and Guidelines). These standards provide a framework to ensure consistency, transparency, and reliability in conducting LCAs. The four phases and the iterative nature of conducting LCAs are illustrated in Figure 2.

Another relevant standard applicable to WBLCA is the EN 15978 (Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method). This European Standard describes the process and provides calculation rules for the assessment of the environmental performance of buildings, which are similar to the ISO 14040 standard.

Through our Pilot, we have interpreted the four LCA phases outlined by the ISO 14040 standard series as follows:

- **Goal and Scope Definition** – In this phase, practitioners determine the purpose of the assessment, which components of the building will be assessed, and over which life cycle stages, among other parameters.

- **Life Cycle Inventory Analysis (LCI) –** In this phase, practitioners compile and quantify inputs and outputs of the building's systems and components throughout its life cycle. For building LCAs, practitioners usually quantify the materials and products within the building and use LCA software tools that estimate the rest of the flows within the system.

- **Life Cycle Impact Assessment (LCIA) –** In this phase, practitioners use the LCA tools to evaluate the potential environmental impacts of the elements quantified in the LCI through the chosen impact categories (e.g. GWP in the case of embodied carbon). LCA tools calculate these impacts using data from different public or proprietary databases.

- **Interpretation of LCA –** Practitioners interpret the partial and final results within the context of the overall LCA process and assessment system. Some of the considerations for interpreting results include identifying issues from the LCI and LCIA phases (e.g. data limitations, assumptions and exclusions), evaluating the LCA study itself (e.g. consistency and completeness), and other conclusions, limitations and recommendations.

The procedures described in this section are focused on the first three phases of the LCA framework: 1) goal and scope definition through the assessment parameters; 2) life cycle inventory analysis through the data extraction and quantity calculations; 3) life cycle impact assessment through material mapping, information input into the LCA tool and the output of results. The interpretation phase is briefly discussed and some implications of this phase are mentioned in the context of the first three phases, but it is not the focus of this methodology.

The organization of this section follows the sequence of decisions and procedures involved in data preparation for a WBLCA. Section 2 details key assessment parameters and highlights front-end decisions required before beginning the actual data collection, emphasizing the importance of understanding and defining the LCA scope. Section 3 describes the data preparation methodology through a series of steps, suggesting specific methods of organizing and classifying data. Subsection 3.4 discusses the limitations of this method, including future considerations for the interpretation phase.

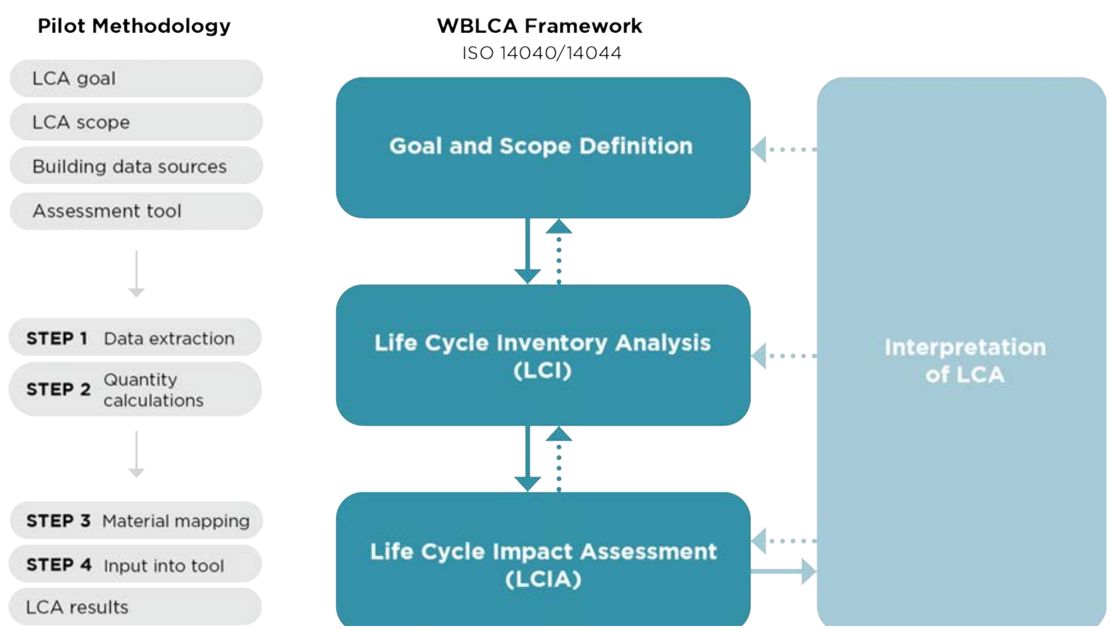


Figure 2: LCA process per ISO 14040:2006 and correlation with the Pilot methodology

2 ASSESSMENT PARAMETERS

Before conducting the LCA, the practitioner must determine the goal and scope of the assessment. These initial decisions set the stage for a successful process by outlining clearly defined parameters, including the LCA goal, scope, timing and data source. LCA results can vary widely based on these parameters, therefore it is important to define them clearly prior to starting the assessment. These factors are described and discussed in the following section.

2.1 LCA goal

LCA Goal – the goal of the LCA must be determined to set the basis for the assessment. An LCA provides insight on the environmental impacts of a building, and this information can be used for different purposes, which commonly include:

- Assessing various design options, from single components to the entire building, during the preliminary design and design development phases.
- Communicating design decisions and their corresponding environmental impacts to stakeholders.
- Demonstrating compliance with building standards or set targets, whether voluntary or required.
- Compiling data for use as a baseline (e.g. singular comparison building) or benchmark for future performance targets.
- Informing academic, industry, or policy research.

Each of these goals requires different considerations for the assessment's scope, data source, tool and input method, and project phase. For example, an LCA to help select between different design options would be conducted towards the beginning of a design process and would probably only include building systems relevant to the options (e.g. the roof system or structural materials). The BoM for a design-decision LCA would use estimates of component sizes and generic industry information about the materials. On the other hand, an LCA to demonstrate that a building meets a certain performance target would be conducted when the design is complete and would include a more comprehensive list of components in the major building systems such as structure, foundation and envelope. This BoM would use exact information on the size and material composition of the specific products used in that building.

Assessment Timing – Depending on the goal, the assessment may be conducted at different points in the project design or construction process, or even after building occupancy. As the building design is developed, the project data sources become progressively more detailed and it is important to identify the appropriate data source and level of development that best supports the purpose of the LCA, whether it be for certification, benchmarking, research, or design decision-making.

For example, an LCA based on early design documents would not reflect the actual building's materials but would be useful for project teams to select between different options, taking environmental impacts into consideration. In contrast, as-built documents that include detailed information on all building elements and components are better suited for reporting on performance, since they provide a more accurate estimate of the actual building material quantities.

2.2 LCA scope

The LCA scope should be well defined to ensure that the breadth, depth and detail of the study are compatible with the goal. LCA scope includes:

- Object of assessment
- System boundary (life cycle stages)
- Reference study period

If the LCA is a comparative assessment for design decision-making or for certain certifications, a functional equivalent should also be defined. The functional equivalent is a baseline building that represents the required characteristics and functionalities of the building to be assessed. This could be an actual or theoretical model building.

Object of Assessment – The object of assessment is defined as the construction elements included in the LCA scope. Broadly, WBLCA typically includes the building's structural and envelope elements (Bowick et al., 2017). These can be described in terms of a building classification system, which breaks down building assemblies into standardized categories and sub-levels, providing an organizational structure for classifying elements.

Building classification systems provide a standardized framework for organizing detailed information about a building's materials, products, and activities. Three common building classification systems used in North America are MasterFormat, UniFormat and OmniClass, which are all supported by the Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC). Each system organizes information differently, although overlap between the systems does exist. Practitioners should use the building classification system that best aligns with their project documentation and selected LCA tool.

When defining the scope, the assembly detail should also be determined. This term refers to the depth of detail, or 'completeness', of the construction elements within the object of assessment. For example, for an object of assessment that contains exterior walls, assembly detail refers to which components or layers within those walls should be included. This consideration is one of the more difficult to prescribe and relies heavily on the purpose of the assessment, the information available from the project data source and the practitioner's interpretation and experience. Maintaining a consistent assembly detail for objects of assessment between projects, such as for benchmarking, would need standardized requirements and detailed guidelines, as well as a rigorous approach to decision-making (e.g. the level of detail used for curtainwall mullions should correspond to the level of detail used for other window and door frames). While determining the assembly detail often occurs on a case-by-case basis due to each building's unique assemblies, Figure 3 illustrates an example of inclusion and exclusions within an assembly.

Level 1	Level 2	Level 3	Level 4	Included materials / assemblies	Excluded materials / assemblies
A. Substructure	A10 Foundations	A1010 Standard Foundations	A1010.10 Wall Foundations A1010.10 Column Foundations A1010.90 Standard Foundation Supplementary Component	Concrete Masonry Treated wood Rebar Insulation	Stirrups Draining materials Filter fabrics Water barrier
		A1020 Special Foundations	A1020.10 Driven Piles A1020.15 Bored Piles A1020.20 Caissons A1020.30 Special Foundation Walls A1020.40 Foundation Anchors A1020.50 Underpinning	Concrete Rebar Insulation	Subbase layer Vapour barrier Waterproofing barrier Framework Expansion/ control joints Finishes
			A1020.60 Raft Foundations		
			A1020.70 Pile Caps		
			A1020.80 Grade Beams		
	A20 Subgrade Enclosures	A2010 Walls for Subgrade Enclosures	A1020.10 Subgrade Enclosure Wall Construction A1020.20 Subgrade Enclosure Wall Interior Skin	Concrete Masonry Rebar Gypsum board Insulation	Vapour barrier Water barrier
			A1020.90 Subgrade Enclosure Wall Supplementary Components		
	A40 Slabs-on-Grade	A4010 Standard Slabs-on-Grade		Concrete Rebar Insulation	Subbase layer Vapour barrier Water barrier Framework Expansion/ control joints Finishes
		A4020 Structural Slabs-on-Grade		Concrete Rebar	Finishes
		A4030 Slab Trenches		Concrete Rebar	Finishes
		A4040 Pits and Bases		Concrete Rebar	Finishes Anchor bolts
		A4090 Slab-on-Grade Supplementary Components	A4090.10 Perimeter Insulation A4090.20 Vapour retarder A4090.30 Waterproofing A4090.50 Mud Slab A4090.60 Subbase Layer	Insulation	
	A60 Water & Gas Mitigation	-	-	-	-
	A90 Substructure Related Activities	-	-	-	-

Figure 3: Example of assembly details included/excluded from the substructure

System Boundary – The system boundary refers to the life cycle stages that are included in the LCA. The diagram below (Figure 4) shows an overview of the building life cycle stages: product, construction process, use, and end-of-life, as well as benefits and loads beyond the building life. It also shows a more detailed breakdown of the modules within each stage. All LCA tools have default system boundaries, which can vary between tools. Some tools allow the users to limit the system boundary or will calculate certain life cycle stages only if the user inputs additional information. A common example is operational energy and water use, which may be within a tool's capacity to include in the LCA results but requires additional information about the building's anticipated operations that the user must input.

Note: Although modules B6 and B7 – operational energy and water use – are part of the LCA system boundary, the results from these modules are excluded when assessing embodied carbon, since these represent the operational emissions of the building and not the embodied emissions.

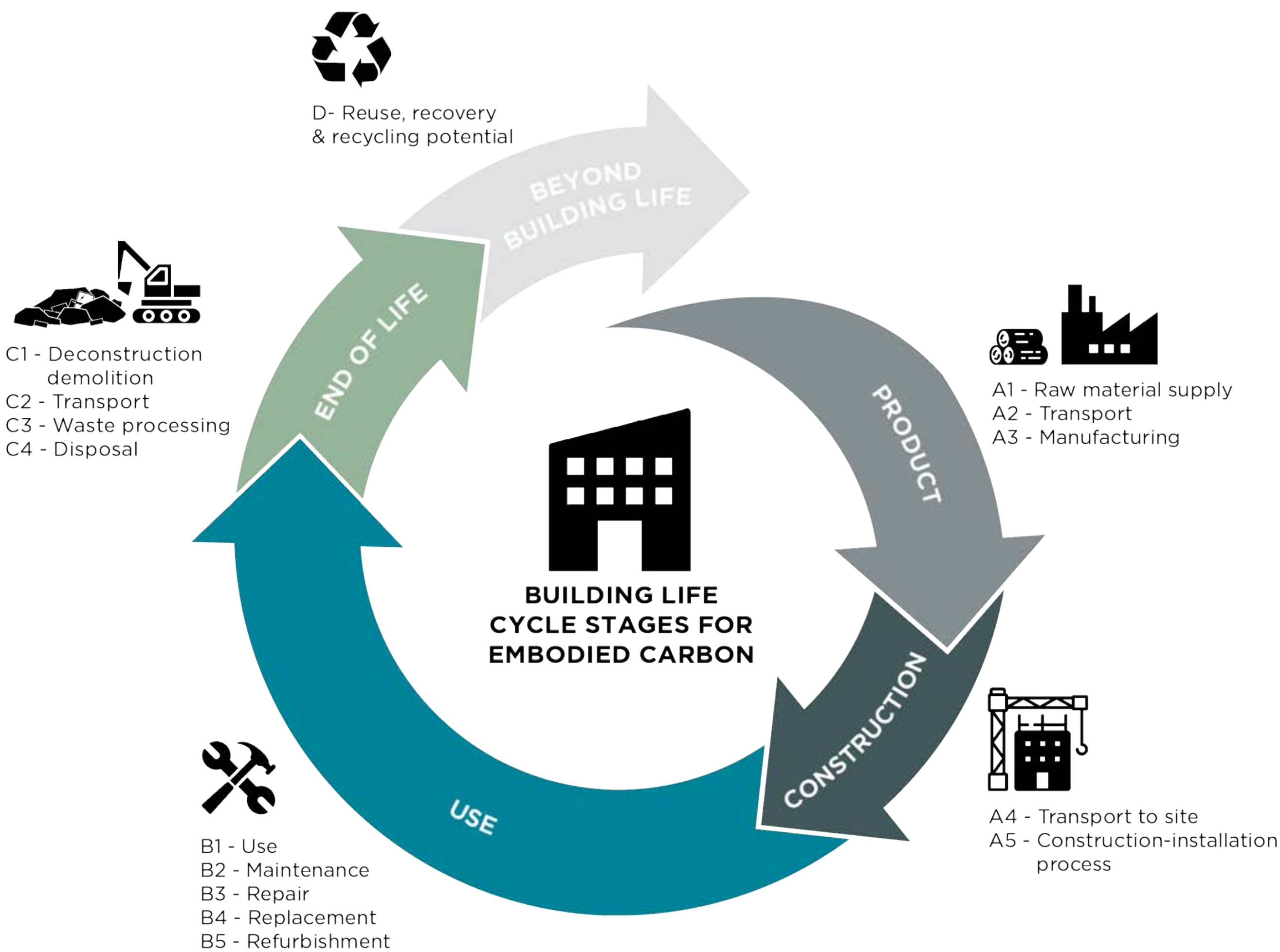


Figure 4: Embodied carbon building life cycle stages and modules per EN 15978:2011

Reference Study Period – The reference study period is the period over which the building is being assessed. The reference study period often corresponds to the required service life of the building. However, it may differ from the required service life depending on the LCA goal or the regulatory or certification requirements for the LCA. In case the required service life and the reference study periods are different, the EN 15978 standard recommends applying a factor to account for the difference between the two.

Whole-building LCA tools allow the practitioner to specify the reference study period, which will only impact the ‘use’ life cycle stage (modules B1-B5 plus B6-B7 when evaluating operational uses). Most buildings in North America have a required service life ranging from 50 to 100 years, or sometimes less.

2.3 Building data sources

The project data source is the point of origin (document, list, model, drawing, etc.) from which practitioners can gather information about the building’s assemblies and material quantities. Project data sources may be further classified as:

- **Primary –** measured quantities, e.g. from a purchase order, purchase receipt, etc.,
- **Project-specific –** quantities derived from building project documentation, e.g. BIM, project drawings, etc.,
- **Product-specific –** data taken from product information such as EPDs and LCAs, or
- **Secondary –** industry-average data from databases, libraries, etc. (National Research Council Canada, 2021).

The data classification represents the level of accuracy of each source. Primary and project-specific data sources usually provide the most detailed and theoretically accurate information about the quantities and materials in the building. Product-specific and secondary sources are not project dependent and are industry averages, approximations and estimates. The level of accuracy, however, is not always directly related to the data quality. For example, the completeness of a measured quantity (primary) may be so poor that other available sources (project-specific, product-specific, or secondary) are a better choice.

The most appropriate data source to use depends on the LCA purpose, the project timing and the availability and quality of information. For example, to conduct LCAs on buildings in the planning and early design phase, it may be necessary to use secondary data as the project-specific materials or quantities may not be specified yet. Conversely, for buildings nearing completion, primary and project-specific data should be available through project drawings, specifications, shop drawings or procurement documents.

Three common project-specific data sources that are widely used to source building information for LCA purposes are project drawings, cost estimates and building information models.

- **Project Drawings –** project drawings typically used to generate a BoM are the architectural and structural sets, including plans, elevations, sections, and details. These can be supplemented by other documents, such as specifications or shop drawings, which provide information on specific materials and quantities. Quantity takeoffs are performed to extract material quantities from these documents often with the help of digital measurement software (e.g. Bluebeam Revu). Using the project drawings as a data source requires knowledge of quantity takeoff methods and common construction assemblies and techniques. It requires professional judgement on the practitioner’s part and can be time-consuming.

- **Cost Estimates –** cost estimates detail the anticipated material quantities and associated material and labour costs of a building. They are typically prepared by a professional cost estimator or construction manager, and the list of material quantities can be used as a data source for conducting an LCA. Data preparation from cost estimates, which are typically arranged according to a standard building classification system, requires minimal processing but will reflect the choices and assumptions of the estimator. In addition, cost estimates are prepared primarily to assess costs and may not necessarily include all relevant materials for estimating environmental impacts.

- **BIM models** – Building information models, also known as BIMs or BIM models, are a virtual 3D representation of a building and contain information and parameters about its design. The modelling software may allow extraction of assembly information and material quantities directly from the 3D model (e.g. via material takeoff schedules in AutoDesk Revit). With BIM models, the composition of the list of materials depends heavily on the model's level of development (LOD)[1] and purpose. For example, BIM models that are only used for visualization purposes might not have all the relevant information to conduct an accurate assessment, as important assembly and component details may have been omitted for ease of modelling. Specialized knowledge of the BIM software is needed to extract the data and determine whether quantities are being aggregated correctly, and further manual calculations are often required for certain materials or assemblies that are missing from the model. While the use of BIM models appears to be straightforward and quick, additional troubleshooting and data processing is often required.

1 BIM LOD is an industry standard that defines various development stages of the building in BIM and is used as a measure of the service level required. It is the equivalent of specifying the design development phase in the creation of project drawings. For example, LOD 100 would correspond to pre-design, LOD 200 to schematic design, LOD 300 to design development, LOD 400 to IFC documentation and LOD 500 to as-built documentation.

2.4 Assessment tools

A range of software tools intended for the building design community are available for conducting WBLCA and for assessing embodied carbon. The selection of a specific tool should be made along with, and based on, the other assessment parameters (i.e. LCA goal and timing, scope and data source). It is also important to consider a specific tool's attributes, such as the system boundary, the data input method and the results format. In addition, each tool draws on its own database of environmental impact information, which will influence the accuracy, applicability and comparability of results.

2.4.1 System boundary

WBLCA Tools – WBLCA tools estimate a building's environmental impacts over the specified reference study period and include detailed impact information for all life cycle stages and a range of environmental impact categories. The system boundary and impact categories may be adjusted by the user based on the study's goal, scope, and input requirements, narrowing its focus to a particular aspect. Three well-established WBLCA tools in North American are Athena Impact Estimator for Buildings (Athena IE4B), One Click LCA, and Tally.

Embodied Carbon Calculators – Embodied carbon calculators offer a more targeted view of a building's impact, focused solely on embodied carbon emissions. These tools often have a more limited system boundary focused only on the embodied carbon emissions from production and based on data from product manufacturers. Carbon assessment tools are not intended to be used to perform a full overview of a building's life cycle impacts, but rather to provide a streamlined approach for practitioners to make design and procurement decisions based on the embodied carbon emissions for specific products or materials. An example of an embodied carbon assessment tool is the Embodied Carbon in Construction Calculator (EC3).

It is important to distinguish the capabilities of these tools based on the system boundary and select the type of tool that meets the goal and scope of the LCA. Embodied carbon calculators that only address upfront carbon emissions from production are better suited to choosing among products within a narrow category and where all other life stages are considered equal. For example, choosing between different manufacturing sources of similar roofing products that will likely have similar life spans and disposal requirements. However, an LCA tool with a more comprehensive system boundary will provide a more accurate assessment of the impacts from different types of roofing systems, with different material compositions, recycling potential and replacement rates.

2.4.2 Data input methods

Each WBLCA tool and embodied carbon calculator has a different user interface and process for inputting material quantity data into the tool. The different data input methods may offer a range of advantages and/or disadvantages, depending on the purpose of the LCA, project data source and scope of the assessment. A selection of common input methods from popular WBLCA tools in North America is discussed below.

BoM Input Method – The BoM input method allows users to upload or manually enter their compiled list of material types, quantities, and other relevant data. While each LCA tool has its own unique materials database and may require different levels of specificity, this input method is relatively simple provided the data processing has been largely completed prior to input. The BoM input method requires a thorough accounting of relevant material quantities present in the project and therefore requires a consistent approach to data preparation to ensure reliability on inputs and results.

- For Athena IE4B BoM input method, quantities are uploaded via an Excel file, and columns and rows are manually mapped to their corresponding data type. The user then selects or confirms the material categories, types, names, quantities, conversion factors, and units of measure for the table entries.

- One Click LCA and EC3, web-based tools, require manual input of each quantity and selection of materials via drop-down lists or searchable databases. Items are entered one-by-one into their corresponding assembly categories, with the user able to control a wide range of data specific to each item, such as material name, quantity, transport, service life, construction waste, and repair percentages.

BIM-Integrated Input Method –The BIM-integrated input method allows for material quantities to be extracted directly from the BIM model to the LCA tool with little required intermediate data processing, typically in the form of a software plug-in. It requires compatibility between the modelling software and LCA tool software.

- In Tally, an AutoDesk Revit plug-in, users specify material parameters within the project browser which consists of defining reference and takeoff information for each entry in the BIM model to create the BoM. As the design changes, the BoM automatically updates allowing architects and engineers to see in real-time the impact their design choices have on their buildings' environmental impacts (Kieran Timberlake, 2020).

- One Click LCA offers a downloadable Revit plugin that automatically imports the materials and assemblies from the BIM model into One Click LCA. Mapping materials follows a similar procedure as the BoM input for the web-based tool.

Assembly Input Method – The assembly input method is specific to Athena IE4B and is primarily intended for projects in early design development where less detail is known. Instead of material quantities, building assembly data is entered via dialogues in Athena IE4B component categories: roof, wall, floor, foundations, and columns and beams. Input data varies, but often requires specification of the assembly type, its sub-components, and characteristics such as dimensions, spans, spacing, loading, strength, assembly layers, and opening sizes. The project data source, either drawings or models, must be robust enough to provide this type of detail. The assembly input method does not adapt well to non-standard, complex, or detailed geometries or assemblies, and limits the user's ability to control the input of certain assemblies and details. For example, column and beam sizes are primarily determined by loading rather than dimension inputs. Athena IE4B assembly input method also adds more details, such as fasteners and finishes, which suggest a more comprehensive picture of the building's materials but is not controlled by the user and is based on assumptions within the tool's internal algorithm.

2.4.3 Results format

Each tool has its way of displaying the LCA results. Results may be broken down by building element, material type, life cycle stage, etc. These might be displayed in an online portal or exported in various file formats, and shown in table or graphic forms. Attention should be given as to how the tool generates the output reports to ensure it will provide the results in the format and level of granularity that is useful for the purpose of the LCA.

2.4.4 Tool databases

Life cycle databases in the background of WBLCA tools and embodied carbon calculators allow them to deliver sophisticated LCA results without requiring users to be LCA experts. This underlying data addresses the environmental impacts of materials and products, and may also include data on energy resources, processes (e.g. construction activities), and data on assumptions about the future ("scenarios"). These databases may be public or proprietary and are ideally kept up to date as new information becomes available. Sources of data that may be used in the tools include life cycle inventory data, scenario data and environmental product declarations (EPDs).

LCI data – A life cycle inventory database is a collection of detailed inventory data for many products, processes and materials. The data is a compilation of the input and output flows for each product system. The flows include the energy, water and resource inputs to the product system, and the outputs to air, land and water. This data is the foundation of life cycle assessment – the inventory data is assessed using a life cycle impact assessment method to determine the consequences of the flows on environmental impact categories such as global warming potential. Some WBLCA tools rely on LCI data as the primary underlying data source.

Scenario data – For WBLCA to cover all the life cycle stages, scenario information is needed. This includes assumptions about transportation distances and modes for delivery of products to the construction site, energy use in construction, repair and replacement schedules for products, maintenance, disposition of the building materials at end of life, and landfill dynamics. Some of this information can be input by the user (if known), however, many tools include these standardized assumptions as a background dataset.

EPDs – An environmental product declaration is an independently verified document that provides a summary of LCA results, based on applicable product category rules (PCR) and typically in compliance with relevant standards including ISO 21930, EN 15804 and ISO 14025. There are several different types of EPDs. One primary distinction is life cycle stages included in the results; many EPDs are cradle-to-gate only (the A1-A3 modules). Other EPDs are "cradle-to-gate with options", which means A1-A3 plus some of the other stages. An EPD can also be cradle-to-grave, although this is rarely seen at present. Another key distinction is between EPDs that represent the average for a group of similar products, sometimes called "industry-average" EPDs, and EPDs that are specific to a particular product and a manufacturing site, sometimes called "product-specific" EPDs. Some embodied carbon calculators and WBLCA tools rely on EPDs as their primary source of data.

3

BOM GENERATION METHODOLOGY FOR WBLCA

3.1 BoM classification

The methodology developed through the Embodied Carbon Pilot is for practitioners to generate a BoM for input into a WBLCA tool. The BoM is the estimated quantity of materials included in the building scope, typically excluding construction by-product waste material. However, additional clarification is required as there are multiple steps to developing a BoM for input into an LCA tool, each of which produces a list of material quantities that could be classified as a BoM. The breakdown of these different classifications is detailed below in order of the process's progression and includes four different types of BoM data: Raw Data, Building BoM, Modified BoM, and Output BoM.

Raw Data – This is the data extracted directly from the project data source with no significant processing. Raw Data typically encompasses material quantities that:

- Include unnecessary information for LCA purposes (e.g. costing data or materials beyond the LCA scope)
- Require further breakdown of assemblies (e.g. wall assemblies that need to be broken down into their material layers)
- Require calculation or translation into standard units (e.g. calculating the volume of a beam from given dimensions)
- Require organization or formatting (e.g. grouping into UniFormat divisions)
- Require material selection or further clarification (e.g. specifying a wood column as GLT)

Building BoM – After the Raw Data is processed, it becomes the Building BoM. This BoM is the most accurate representation of the materials specified in the building design or contained in the actual building, bounded by the object of assessment scope and level of accuracy from the data source. It is presented as a list of materials shown in commonly used units and usually organized according to UniFormat or MasterFormat. The Building BoM represents the material quantities of the building of interest and, therefore, is the BoM that should be used for comparison between projects and collected for benchmarking.

Modified BoM – Once the LCA tool is selected, the Building BoM is then transformed into the Modified BoM by mapping the actual building materials to the options available in the WBLCA tool's database. This mapping step creates a list of material quantities that is ready to be input into and assessed by the WBLCA tool. This mapping can be done manually or may be a function of the tool itself. Either way, the replacements and alterations should be documented to differentiate the Building BoM from the Modified BoM. The materials listed in the Modified BoM sometimes require:

- Greater specificity (e.g. specifying the concrete strength)
- Less specificity (e.g. choosing a generic material like rigid insulation instead of proprietary manufacturer product name)
- Adjustment of quantities or units (e.g. adjusting the multiplication factor based on the given gypsum wall board thicknesses in the LCA tool's materials database)

- Substitution (e.g. using steel wall cladding as a proxy for zinc panels, or dividing a compound material like fibreglass insulation with foil facer into two separate materials)
- Exclusion (e.g. eliminating materials/ assemblies that don't have reasonable approximations in the materials database).

Output BoM – After the Modified BoM is input into the LCA tool, the tool's internal algorithm may apply further modifications to the material quantities. It is important to distinguish the Output BoM from the others, as these further modifications are performed automatically by the LCA tool, not the practitioner, and therefore contain assumptions that may be harder to track than those in previous steps. These modifications can include:

- Addition of construction waste factors
- Alterations to the units of measure
- Addition of extra materials (e.g. paint, screws, connections, etc. added through Athena IE4B assembly input method)

The diagram below (Figure 5) depicts the type of data or BoM created according to the point in the BoM generation process suggested in this section. These steps are described in detail in Section 3.3.

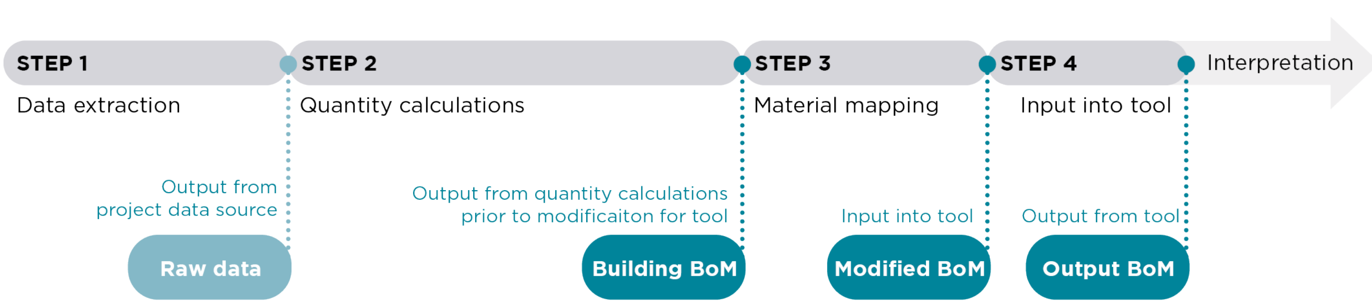


Figure 5: BoM generation process and the BoMs produced in each step

3.2 Translation between building classification systems

Standardizing the building organization system for the Building BoM, prior to modification for input into the LCA tool, is necessary to ensure accuracy of the BoM, consistency between different projects' BoMs for benchmarking and effective comparison against set industry or policy standards. LCA tools categorize material inputs and results outputs using either an industry-standard building classification system, a modified version of such, or a unique system of their own development. The classification system used for project documentation may or may not match the classification system required by the LCA tool. If it does not then the practitioner must convert the information into the appropriate classification system.

The Pilot used UniFormat as the classification system for organizing the Raw Data and Building BoM since it is most commonly used for cost estimates (Afsari and Eastman, 2016) and organizes construction systems and assemblies as functional elements (CSI and CSC, 2010). Additionally, since UniFormat is an industry-standard classification system, it provides a consistent format for project data sources and the assemblies included in the assessment scope.

All the assessment tools mentioned in this section follow their own unique organization and grouping, and the translation between systems should be documented as part of the conversion from Building BoM to Modified BoM. Translating between two systems can lead to the misclassification of building elements, potentially skewing the LCA results, so the documentation of decisions is especially important. Additionally, the use of different building classification systems or inconsistent translation between systems affects the comparability of BoM between projects.

3.3 BoM generation process

The BoM generation process is composed of four steps based on the BoM input method, which produces the four types of BoM listed in Section 3.1. The steps are:

- **STEP 1: Data extraction -** Material quantities are extracted from the project data source. Assemblies within the object of assessment are organized in Excel, creating the project's Raw Data.
- **STEP 2: Quantity calculations –** Calculations are performed to convert the material quantities from the Raw Data into commonly used units, then consolidated into the Building BoM.
- **STEP 3: Material mapping –** Materials from the Building BoM are matched to the closest materials available in the LCA tool's database and assigned to categories based on the tool's classification system, creating the Modified BoM.
- **STEP 4: Input into the tool –** The Modified BoM is input into the tool. The environmental impact results, and the corresponding Output BoM, are exported from the tool.

Throughout Phase 1 of the Pilot, the research team developed prototype Excel templates to simplify and consolidate data, with the added benefit of enhancing legibility and transparency to the assessment inputs and results. The templates help track the object of assessment and assembly detail, translate between different construction classification systems, and provide a consistent approach to calculations.

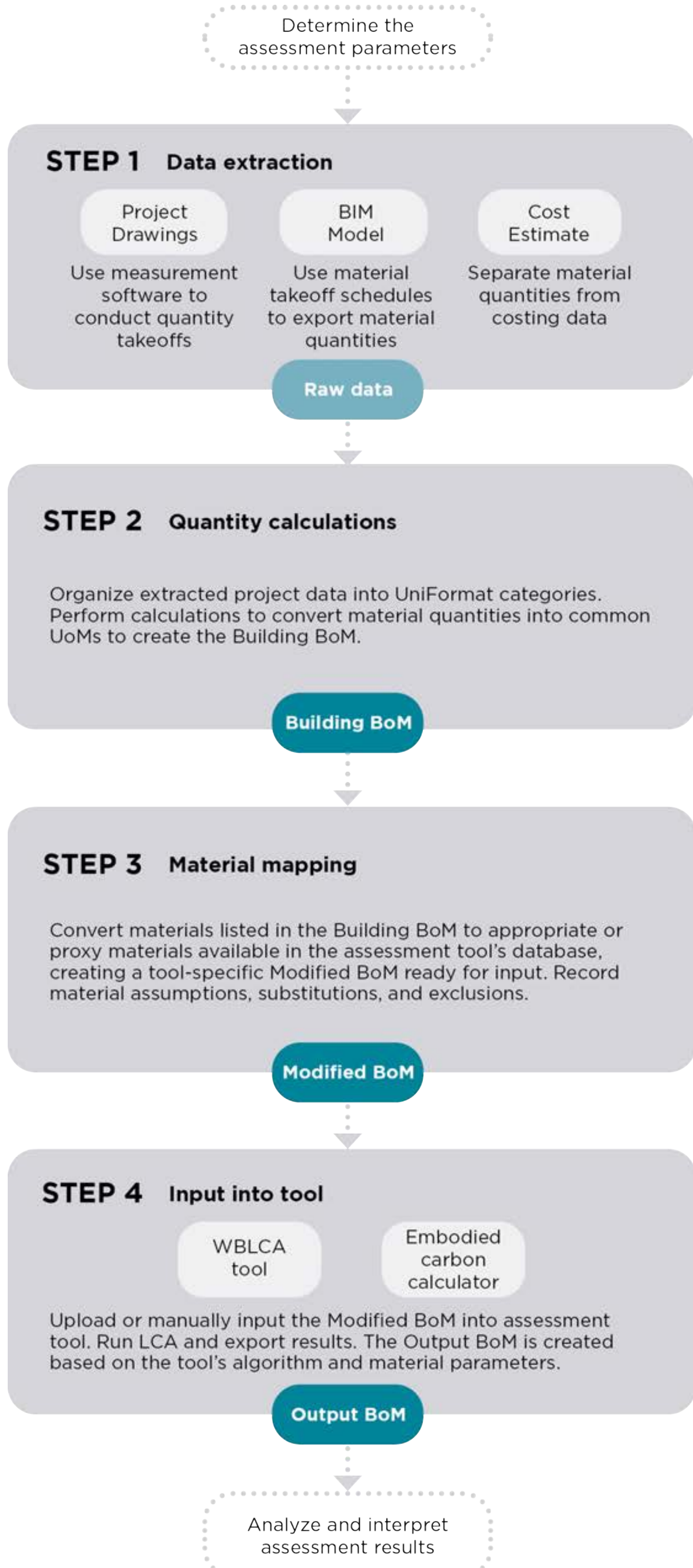


Figure 6: Overview of BoM generation methodology for building LCA

STEP 1

Data Extraction

Project data extraction is the process of converting information from project documents, such as drawings or models, into a preliminary list of materials (i.e. Raw Data). While the specific process will vary by project data source and tools, there are common considerations and steps.

Preparation

Before extracting the material data from the project data source, practitioners should confirm the scope of the assessment, and ensure that the appropriate information and tools are available:

- Verify that the project data sources contain sufficient information, are complete, and represent a consistent building design development (i.e. all project drawings are from the same design phase). If the project data source is not complete or lacking details, consider altering the LCA scope as necessary.
- Define the object of assessment and required level of assembly detail. Building assemblies within the scope should be chosen in accordance with the LCA purpose and recorded by the classification system category in a table or list. Determining the assembly detail should follow consistent logic.
- Ensure that necessary software for data extraction, processing, and organization is installed. Examples of software per project data source include:
  - Project Drawings: Measurement software (e.g. Bluebeam Revu), PDF viewer (e.g. Adobe Acrobat), and Excel
  - BIM Model: BIM software (e.g. Revit) and Excel
  - Cost Estimates: PDF viewer and editor (e.g. Adobe Acrobat Pro) and Excel

Project Data Extraction

Extract the materials information from the project data source and export to Excel. The data extraction process will vary depending on the project-specific data source and software.

Project Drawings – Perform quantity takeoffs from architectural and structural drawings with the use of measurement software like Bluebeam Revu. Work through the object of assessment categories to gather data for relevant assemblies, selecting appropriate drawing types (e.g. elevations) and measurements (e.g. area). Use a consistent and descriptive naming convention for assemblies to keep measurements organized (e.g. Wall Type 1_South) and include the relevant building classification system division for all assemblies that can be clearly distinguished at this stage. Include clear labels with assembly locations to help with sorting in the next step (e.g. label columns and beams in terms of their floor level or supported assembly). Export data to Excel, using an intermediate CSV format if necessary.

BIM Model – Create a material takeoff schedule directly in the BIM software (AutoDesk Revit), selecting appropriate data columns (e.g. family, type, material name, quantity, etc.). Export schedule to Excel, using an intermediate CSV format if necessary.

Cost Estimate – Select relevant pages of the cost estimate that contain material quantity estimations and transfer them to Excel. If the cost estimate is in PDF, then transferring to Excel may be done automatically, but if it is given in a different format, manual input may be necessary.

Once the project data has been input into Excel, refine the extracted material quantities. Add column headings, delete any unnecessary data, sort data by preferred relevance, and fill in data gaps (checking the project data source if necessary). The measurements, quantities, and other data in this table are now referred to as the Raw Data.

STEP 2

Quantity Calculations

Practitioners should perform quantity calculations to convert the material quantities from the Raw Data into commonly used units, then consolidated the data into the Building BoM. A suggested unit of measure is given for each generic material category which allows for a better representation of the building's material quantities.

Quantity Calculations

Calculate material quantities using an appropriate unit of measure for each material or assembly type.

Project Drawings – Copy the measured quantities into the relevant building classification systems divisions and categories under their respective variable column. Begin filling in the necessary missing material properties or measurements to arrive at the final desired unit of measure (UoM).

For example, if the value measured for concrete while doing quantity takeoffs was in units of area (m^2), the user will need to determine the thickness of concrete (m) and density (kg/m^3) to obtain the mass in units of kg.

BIM Model – Fill in the necessary missing material properties or measurements from the material takeoff list to arrive at the final desired UoM. Depending on the level of development of the BIM model, certain details may be missing that are included in the object of assessment or the chosen assembly detail. If this is the case, practitioners will need to calculate detailed quantities based on other project data sources or revise the LCA scope.

For example, if steel reinforcement for a concrete slab-on-grade foundation was not included in the BIM model, one must rely on the dimensions of the slab and specifications of the rebar size and spacing to calculate the total mass of rebar in the slab. Alternatively, a reinforcement ratio in the concrete could be estimated by those with more knowledge of common construction practices/standards.

Cost Estimate – If the material units given are not in the desired unit of measure, perform the necessary calculations and note the parameters used.

Sum identical materials in the same assembly group to achieve one final aggregate material quantity. Compile all finalized material quantities in their respective assembly groups in a separate Excel sheet to create the Building BoM.

STEP 3

Material Mapping

Practitioners must map the materials from the Building BoM to the materials available to the LCA tool's database and assign them to categories based on the tool's classification system, creating the Modified BoM. It is important to record assumptions and decisions made during this step to document the changes to the Building BoM to adapt to the LCA tool's scope. The changes will influence the LCA results.

Material Mapping

Create or use a list of materials broken down by the tool's categories or open the tool itself and search by each material inquiry to identify materials available in the LCA tool. For tools with large materials databases or frequent updates, it is preferable to search directly in the tool.

Select materials. Move methodically through the materials listed in the Building BoM table, searching the LCA tool's materials database and recording (or 'mapping') materials that are the best representations of the original materials. Simultaneously begin filling in the columns of the Modified BoM table in Excel sheet. Record any assumptions or further clarification required.

Materials may need more or less detail depending on the specificity in the project data source and tool's materials database. This additional information may come from research on specific products or manufacturers and/or the practitioner's experience and judgement.

For materials that do not have a suitable counterpart in the tool's materials database, determine if there is an acceptable alternative for substitution (e.g. using aluminum panels as a proxy for copper). If a workaround cannot be found and the material must be excluded, record the issue in the assumptions column and adjust any changes to the LCA object of assessment.

For any quantities with units different from the tool's required input, convert the quantity to the desired units in the quantity column on the table's right side.

In Athena IE4B, a conversion factor is required for some materials in the tool's database, typically for sheet materials that are listed with given thicknesses (e.g. 50mm rigid insulation in the tool's database requires a conversion factor of 4 if the insulation's true thickness is 200mm). If this is the case, add a column in the Modified BoM table and record conversion factors.

Finalize the Modified BoM table with the material quantities ready for input into the LCA tool. For LCA tools that require a file upload (e.g. Athena IE4B) rather than manual input, create a new Excel sheet (Final LCA Input) containing only the Modified BoM material selections, quantities, and other required input parameters. This allows for easier input into the LCA tool and further consolidation of material items if needed.

STEP 4

Input into LCA Tool

The practitioner must upload or manually enter the Modified BoM data into the LCA tool software. The environmental impact results, and the corresponding Output BoM, are exported from the tool.

Preparation

When starting a new project in an LCA tool, general building information is required to accurately assess the environmental impacts. Ensure that this information and its sources are recorded.

In the selected tool, specify general building information such as location, construction type, study period, and Gross Floor Area (GFA) as requested by the tool interface.

The GFA used for LCA purposes should be consistent with the object of assessment and include all areas for which materials are being quantified. If the data source lists a GFA that excludes parkades or non-heated areas, for example, the recommendation is for the GFA to be recalculated to correspond with the object of assessment. This is particularly important if the results will be reported as a rate of a unit of area (e.g. kg CO_2 eq./m^2).

Input into LCA tool

Input the Modified BoM into the selected LCA tool. Note any additional inputs required by the tool to calculate certain life cycle stages. For example, Tally only calculates the impacts from construction and installation (module A5) if the user inputs data about the anticipated or measured energy and water consumed on-site during the construction installation process.

- Upload or manually input the Modified BoM into the selected LCA tool. Record any changes made to the Modified BoM within the tool, such as the renaming of a material.
- Run the LCA.
- Export the generated results in the desired format. Excel is preferred for further analysis but more visual graphs or charts may be more useful for communications purposes.

It is important to conduct a preliminary review of the results by checking for large discrepancies in material quantities from the Modified BoM or incorrectly calculated life cycle stage impacts. Additional steps, such as sensitivity analysis, contribution analysis and/or peer reviews may be performed to validate results, however, these are beyond the scope of this methodology. Practitioners should review the results along with the information from the input process to confirm that the results make sense and recognize that the results are estimates only.

3.4 Methodology limitations

There are othr aspects of the LCA process that are not addressed by the proposed methodology, including the interpretation of the results of the impact assessment, the fourth LCA phase as defined by ISO 14040:2006. According to this standard, the outcome of the interpretation phase should consist of identification of significant issues, evaluation of the assessment process, and conclusions, limitations and recommendations.

More guidance is needed to help practitioners interpret and use the results of WBLCA and embodied carbon assessments. Both the results themselves and the way these are reported can vary widely depending on the parameters, tools and methodology chosen by the user. Additionally, these parameters contain varying ranges of uncertainty, which is carried through the material quantities in the BoM and into the environmental impacts results from the tools. To partially address this uncertainty, sensitivity analyses can be used to estimate the impact of varying the inputs in the LCA results. These analyses can be performed by varying different material quantity inputs and observing the effect on the environmental impact results or by analyzing the proportional contribution of different materials to identify if one is overly contributing to a certain impact. Uncertainty is inherent in the LCA process and yet specific methods, guidance, and policy for addressing the confidence of WBLCA results remain largely undeveloped.

The methodology developed for the Pilot focused on the input processes of an LCA, specifically the procedures required to generate a BoM and prepare the data for input into an LCA tool, as well as the parameters that users should define before moving into the inventory analysis and impact assessment phases. In Section 5, we will analyze the variations in results only as a way to understand the importance of the different parameters and processes of the LCAs. We have not developed any guidance for the interpretation of results. This is an important area for future research and policy.

Currently, there is no guidance on a consistent approach to the collection, organization, and calculation of material quantities for the practice of WBLCA in North America. The methodology developed through this Pilot and detailed in this section is an attempt to bridge a procedural gap between LCA practice and policy development by providing a detailed breakdown of the data preparation necessary to create a BoM for input into an LCA tool. The distinction between different types of BoM in this methodology aims to clarify the changes to the data between the inputs and outputs of each step in the process, which is often not clear. Similarly, the division of steps in the process is intended to more clearly articulate the scope of work, decisions and assumptions inherent in conducting an LCA.

Additional research and discussion on guidelines or best-practice documents for the generation of BoMs for use in LCAs or embodied carbon assessments are needed. The methodology and learnings from the Pilot are intended to inform specifications created by policymakers or green building certification programs for project teams to improve the transparency of BoM data and the replicability and usability of WBLCA impact results.

4

PILOT RESULTS

4.1 Assessments overview

Based on the lessons learned from Phase 1 of the Pilot, in Phase 2 the research team developed the methodology in Section 1, which details and refines protocols to quantify the building materials and generate the building's bill of materials. In Phase 2, we applied and tested this methodology by conducting WBLCAs on 7 different buildings ranging from multi-unit residential and student residences, to commercial/office and institutional buildings. We focused on buildings in BC that are nearing design completion, are under construction or were recently completed.

In partnership with the Zero Emission Building Exchange (ZEBx), we gathered project documentation from high-performance building projects that are participating in the Better Buildings BC's Net-Zero Energy-Ready (NZER) Challenge. The NZER Challenge is a provincial incentive program and juried competition that provides support and recognition to builders and developers of multi-family, commercial, and institutional buildings that are designed to achieve the top tier of the BC Energy Step Code (or Passive House standard). In exchange the project teams are expected to share information for research, learning and industry advancement.

Through this program, we collected data for 5 building projects:

- **Carrington View (Building A)** - The Carrington View Apartments complex is a three-building, 240-unit, solar-powered complex located in West Kelowna, BC. Building A is a four-storey high-performance, wood-frame building and is the only one of the three that is part of the NZER Challenge.

- **SFU Parcel 21** - Located in the SFU Burnaby Campus, Parcel 21 is an energy-efficient residence with 80 affordable rental apartment units for students. It is composed of a four-storey wood-frame building on a concrete parkade and a six-storey wood-frame building.

- **2150 Keith Drive** - 2150 Keith Drive is a ten-storey office building planned for East Vancouver's False Creek Flats, with an estimated completion date in 2021. The building's structure is nine storeys of mass timber over a concrete base.

- **825 Pacific** - 825 Pacific is a seven-storey, multi-purpose arts and culture hub to be located in downtown Vancouver, with an estimated completion date in 2021. It is designed to Passive House standards.

- **UBCO Skeena** - Located on UBC's Okanagan campus (UBCO), the Skeena Residence provides housing for 220 first-year students and is targeting Passive House certification. The six-storey building has five levels of wood frame construction built above a concrete ground floor.

In addition to these 5 buildings, we also collected project documentation from 2 other buildings located on the UBC campus:

- **TRIUMF Institute for Advanced Medical Isotopes (IAMI) -** Located at UBC's Vancouver campus, IAMI is a specialized, state-of-the-art facility for research on next-generation medical isotopes and radiopharmaceuticals. The building is a five-storey concrete building, with 2 levels below grade.
- **Brock Commons Phase 2 (South Tower) -** Brock Commons is an academic and student housing complex on UBC's Vancouver campus. Targeting completion in 2021, the South Tower is a 13-storey concrete building that will provide housing for 600 students.

These buildings have a range of uses, sizes and structural materials, and varying levels of energy performance. Most of the projects had BIM models which we used as the main data source to create the Building BoM. For the one building where a BIM model was not available, we used a detailed cost estimate which included building material quantities. The variability in types of buildings and data sources was a key aspect that we wanted to explore in Phase 2.

The WBLCAs were focused on estimating the building's embodied carbon and were conducted to develop a more detailed understanding of the requirements of the BoM generation processes, and how project data sources and tools contribute to variations in results.

In total, the team conducted 9 assessments on the 7 buildings, using different project data sources and WBLCA tools, as shown in Figure 7. The majority of the assessments were conducted using Athena IE4B. For TRIUMF IAMI and UBCO Skeena, we conducted assessments using the same Building BoM and two different assessment tools: Athena IE4B and Tally. We also conducted one other assessment using Tally and one using One Click LCA.

The use of different project data sources and tools resulted in differences in the BoM calculation methods and systems boundaries, all of which contributed to variations in the results. These results for each of the assessments are described in detail in the following LCA profiles in this section.

DATA SOURCE	**WBLCA TOOL**		
	Athena IE4B	Tally	One Click LCA
Cost estimate	Carrington View (A)		
BIM Model	825 Pacific (A)	2150 Keith Drive (T)	Brock Commons (1C)
	TRIUMF IAMI (A)	TRIUMF IAMI (T)	
	UBCO Skeena (A)	UBCO Skeena (T)	
	SFU Parcel 21 (A)		

Figure 7: Assessments organized by data source and LCA tool

4.2 Assessments scope

In order to be as consistent as possible in the assessments, we applied a similar scope to all the WBLCA.

As noted above, the project data sources were mostly BIM models, with one Cost Estimate. Although the BIM models of each project varied in level of development, most of them included sufficient information on the architectural and structural elements.

The object of assessment included the building foundation, structure (floors and ceilings), envelope, roof, interior walls and partitions (all layers up to gypsum board), stairs, doors and windows. Although it was generally not included in the BIM models, we included reinforcing steel on concrete structural elements for all buildings. Mechanical and electrical systems, furnishings, and finishes like paint were excluded from all of the assessments.

The systems boundary included the product, construction, use and end of life stages. The system boundary is dependent on the LCA tools and we selected a boundary that could be consistently used across the different tools. We excluded Module D Benefits Beyond the Life of the Building for Athena IE4B and Tally, and selected the option that excludes biogenic carbon for Tally.

We chose 60 years as the reference study period for all the assessments. Some buildings had a longer design service life and others did not have an identified service life, but 60 years was a good average for North American buildings, recognizing that the actual service life will vary according to use, type of structure and owner.

The research team created the following LCA profiles to display the results of each assessment and to be used as a communication tool by the project team and other stakeholders. These assessments were conducted for research purposes and should not be used for reporting or policy compliance purposes. Results from different assessments may not be comparable to each other; the highest impact categories noted in the LCA profiles represent the most prominent assembly, life cycle stage and material for each assessment, which indicate potential areas for improvement in embodied carbon emissions.


photo credit - DIALOG

EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT

2150 KEITH DRIVE

353
kg CO_2 eq./m²

ARCHITECT | **DIALOG**
STRUCTURAL ENGINEER | **Fast + Epp**
YEAR COMPLETED | **Under construction (2021)**
LOCATION | **Vancouver, BC**
USE | **Offices**
GFA | **24,555 m²**
TOTAL STORIES | **10**
HEIGHT | **60.5 m**
PRIMARY STRUCTURE | **Mass timber and concrete hybrid**

Located in Vancouver BC, 2150 Keith Drive is an innovative 10-storey office building that will include office spaces, flexible meeting areas, rooftop deck, and wellness and social spaces. The hybrid structure includes nine levels of mass timber construction above a concrete ground floor. The structure also features a unique honeycomb curtainwall façade design that provides structural benefits, creates balconies and outdoor spaces and gives the building its signature look. Mass timber elements within the structure include glulam beams, columns and braces, and cross laminated timber walls and floor panels, that were sustainably and locally sourced. The building project is targeting high performance environmental standards like LEED Gold certification.

LCA PARAMETERS

PROJECT DATA SOURCE
BIM model

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Tally (Version 2020.06.09.01)

DATE OF ASSESSMENT
February 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls, windows and doors
Interior walls, doors and ceilings
Roof

NOTABLE EXCLUSIONS
Interior finishes

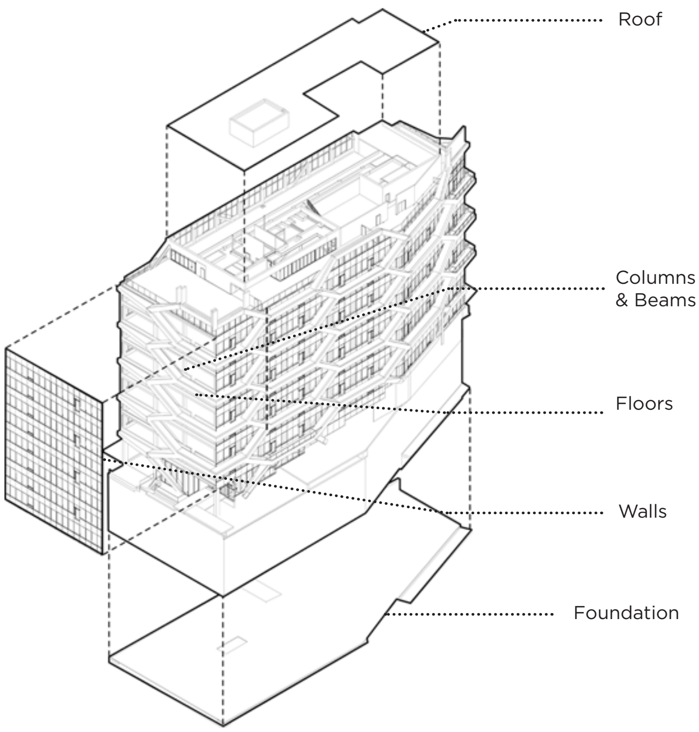
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4)
Use (B2-B5), End of Life (C2-C4)

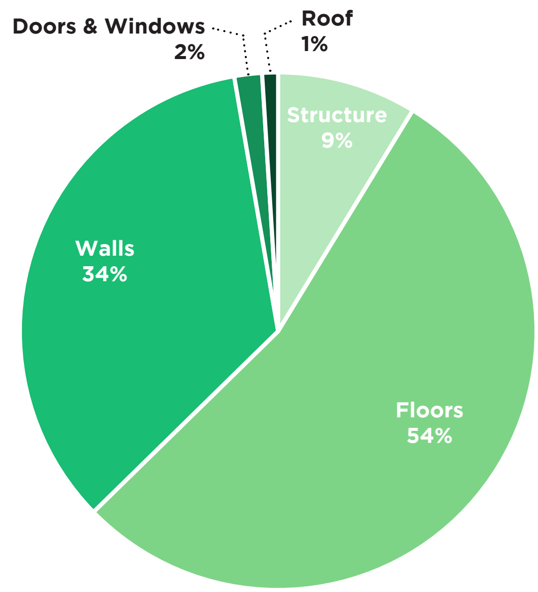
TOTAL GWP
8,669,915
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
FLOORS

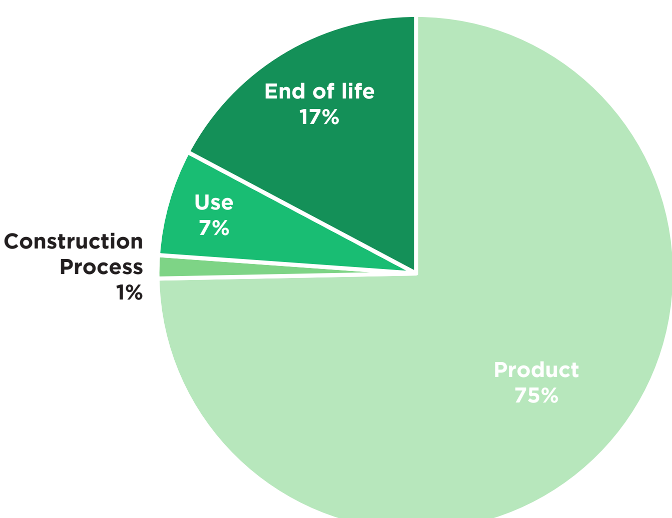
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
CONCRETE

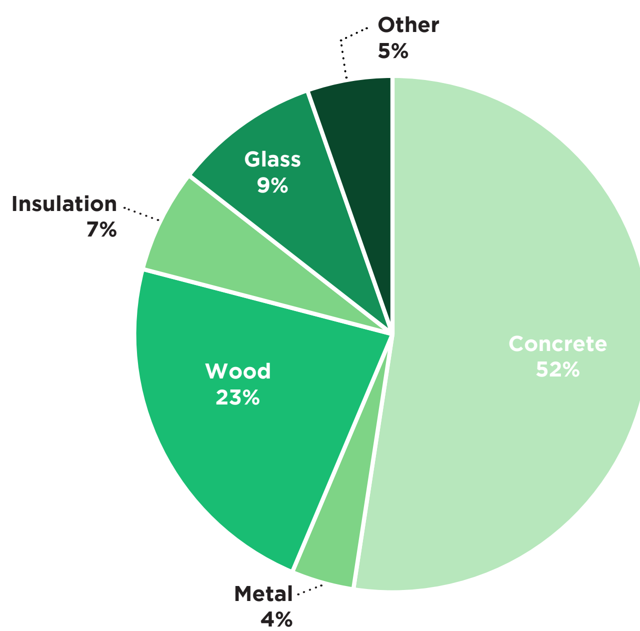




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

This assessment was conducted for research purposes and should not be used for reporting or policy compliance purposes. Results from different assessments may not be comparable to each other; the highest impact categories noted above represent the most prominent assembly, life cycle stage and material for each assessment, which indicate potential areas for improvement in embodied carbon emissions.

EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT

825 PACIFIC

430
kg CO_2 eq./m^2

DEVELOPER | **Grosvenor Americas**
ARCHITECT | **IBI Group Architects**
STRUCTURAL ENGINEER | **DIALOG**
YEAR COMPLETED | **Under Construction (2021)**
LOCATION | **Vancouver, BC**
USE | **Cultural hub**
GFA | **2,704 m^2**
TOTAL STORIES | **7**
HEIGHT | **33.1 m**
PRIMARY STRUCTURE | **Concrete and Steel**

Located in Downtown Vancouver 825 Pacific is a multi-purpose arts and culture hub for the local community that will accommodate production studios, gallery and office space. Upon completion, anticipated Summer 2021, the building will be provided to the City of Vancouver to support the City's initiative of creating and repurposing spaces for arts and culture. The seven-storey, concrete and steel frame building will be constructed to Passive House standards with unique envelope solutions that meet the energy targets.

LCA PARAMETERS

PROJECT DATA SOURCE
BIM model

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Athena IE4B (Version 5.4.0101)

DATE OF ASSESSMENT
January 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls, windows and doors
Interior walls, doors and ceilings
Roof

NOTABLE EXCLUSIONS
Interior finishes

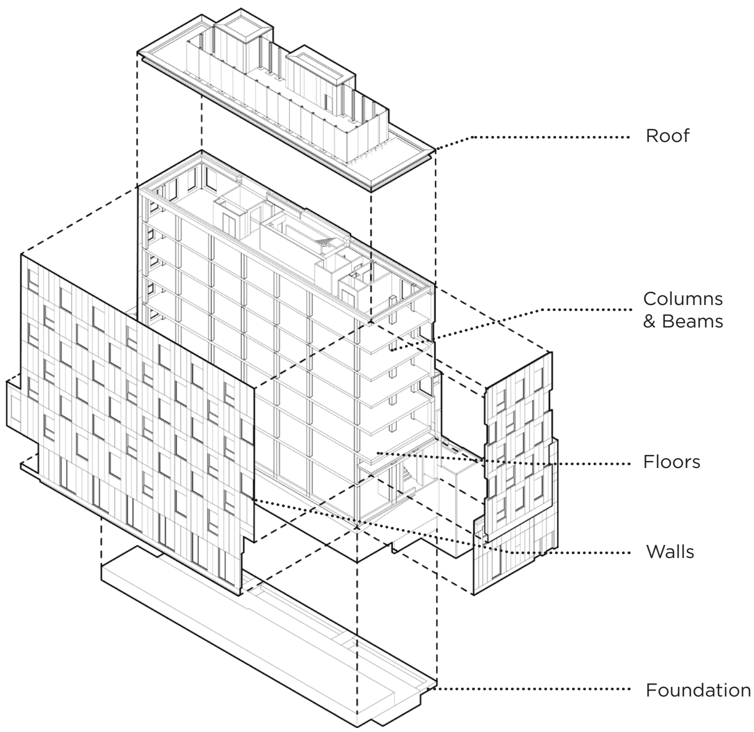
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4-A5)
Use (B2, B4), End of Life (C1-C2, C4)

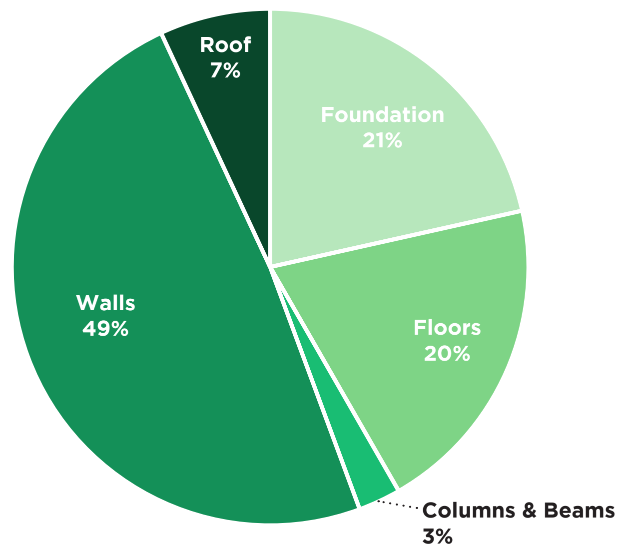
TOTAL GWP
1,164,508
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
WALLS

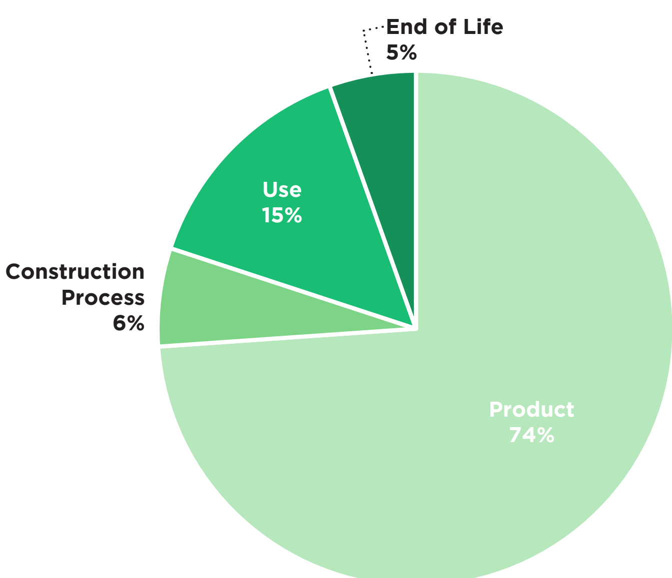
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
CONCRETE

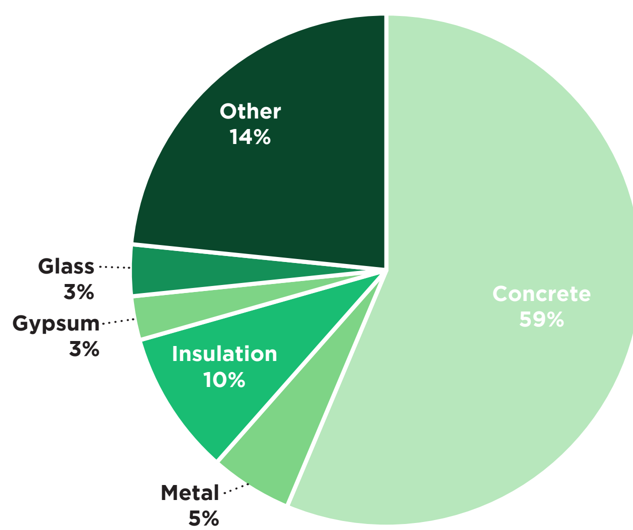




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

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EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT

443
kg CO_2 eq./m²

BROCK COMMONS PHASE 2 (SOUTH TOWER)

ARCHITECT | **HCMA Architecture + Design**
STRUCTURAL ENGINEER | **WHM Structural Engineers**
YEAR COMPLETED | **Under Design (2022)**
LOCATION | **UBC Vancouver Campus, BC**
USE | **Mixed-use residential / academic**
GFA | **19,543 m²**
TOTAL STORIES | **13**
PRIMARY STRUCTURE | **Concrete**

Brock Commons Phase 2, located at UBC Vancouver campus, is an academic and student housing hub that will provide up to 600 student beds, as well as institutional, childcare and community spaces. The development includes a concrete 18-storey north tower and a concrete 13-storey south tower. The north tower will have majority of student accommodation, while the south tower will contain majority of institutional spaces with a focus on student services and wellness. The project has set several sustainability goals in relation to environmental impacts and social well-being, such as LEED Gold certification, climate adaptation, biodiversity protection, water efficiency and use of sustainable materials and resources.

LCA PARAMETERS

PROJECT DATA SOURCE
Architectural BIM model

PROJECT PHASE
Design development (tender)

LCA STUDY PERIOD
60 years

TOOL
One Click LCA (Student version, 2020)

DATE OF ASSESSMENT
February 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation
Floors
Exterior walls
Interior walls
Roof

NOTABLE EXCLUSIONS
Windows, doors, stairs
Interior finishes

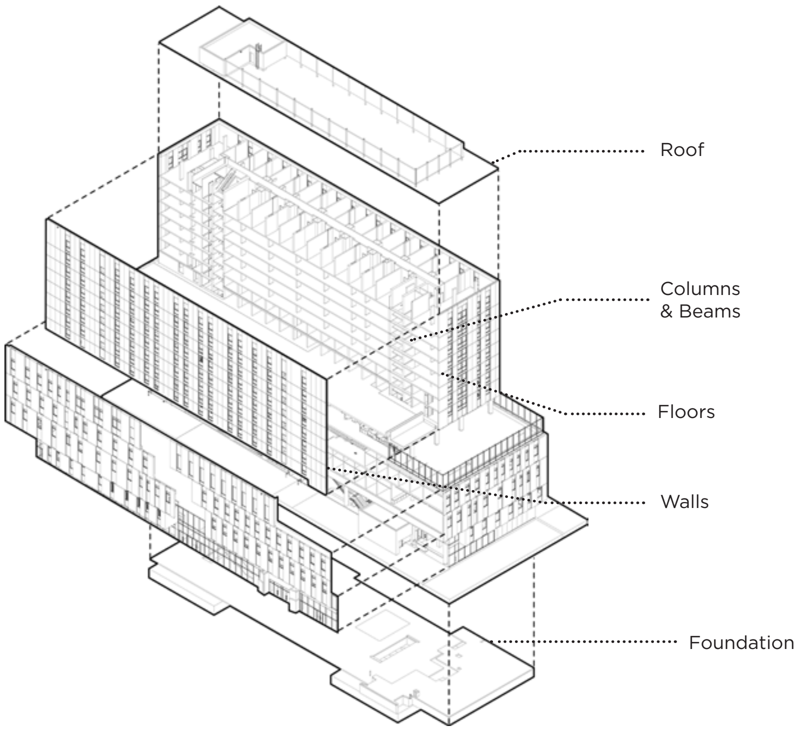
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4)
Use (B1-B5), End of Life (C1-C4)

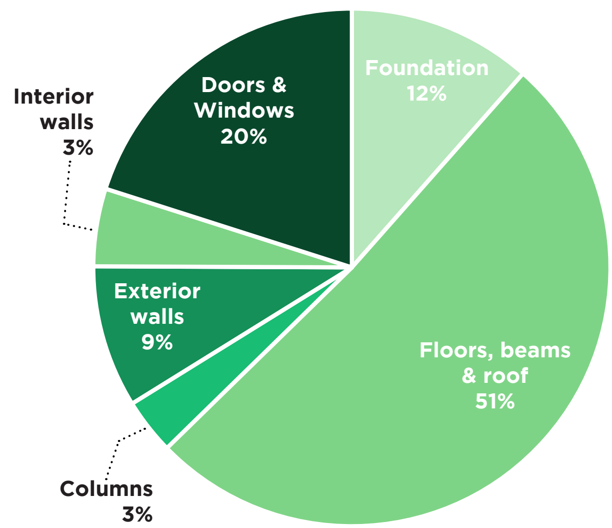
TOTAL GWP
8,659,018
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
FLOORS+ROOF

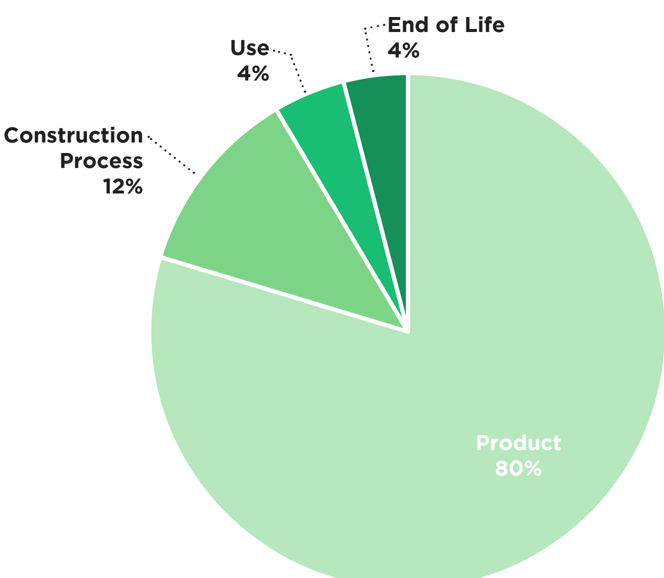
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
CONCRETE

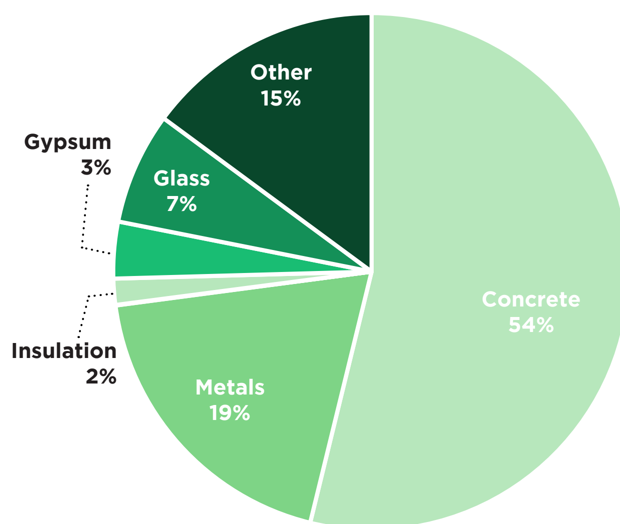




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

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121
kg CO_2 eq./m²

EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT

CARRINGTON VIEW (BUILDING A)

DEVELOPER | **Highstreet Ventures**
ARCHITECT | **WD Fisher Architecture**
STRUCTURAL ENGINEER | **Sorensen Trilogy**
YEAR COMPLETED | **Under Construction (2021)**
LOCATION | **Kelowna, BC**
USE | **Multi-unit residential**
GFA | **7,729 m²**
TOTAL STORIES | **4**
HEIGHT | **16.4 m**
PRIMARY STRUCTURE | **Wood-frame**

Carrington View Building A is a high-performance building that is part of an upcoming multi-unit residential development in West Kelowna. The four storey wood-frame building consist of 186 new rental housing units including studio, 1-bedroom and 2-bedroom suites, and amenities including social lounge, gym, rooftop patio, community garden and meeting rooms. The building also features a high-performance prefabricated wall system and on-site solar power generation.

LCA PARAMETERS

PROJECT DATA SOURCE
Cost estimate (Class C)

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Athena IE4B (Version 5.4.0101)

DATE OF ASSESSMENT
January 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls, windows and doors
Interior walls, doors and ceilings
Roof

NOTABLE EXCLUSIONS
Interior finishes

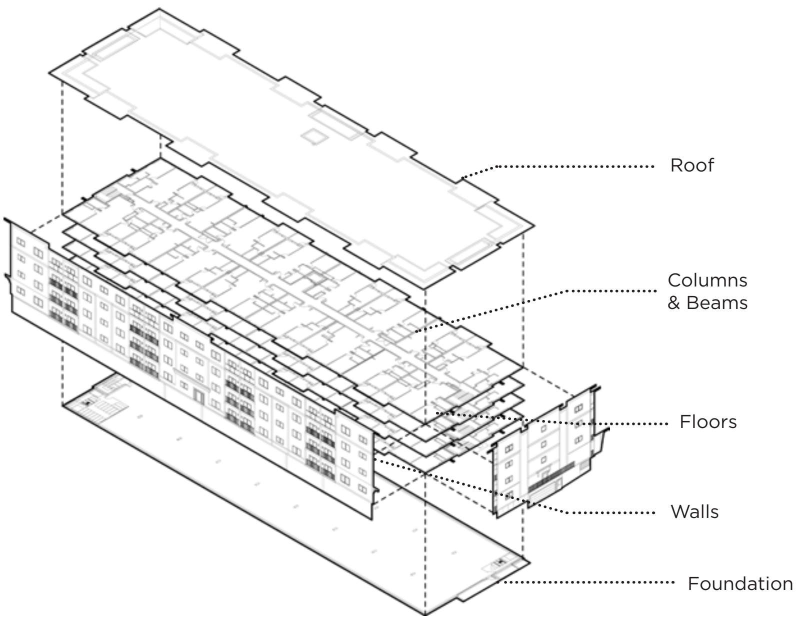
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4-A5)
Use (B2, B4), End of Life (C1-C2, C4)

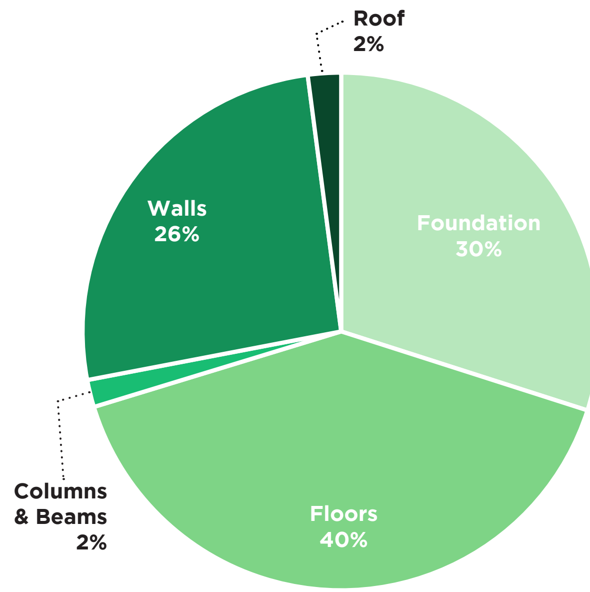
TOTAL GWP
937,126
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
FLOORS

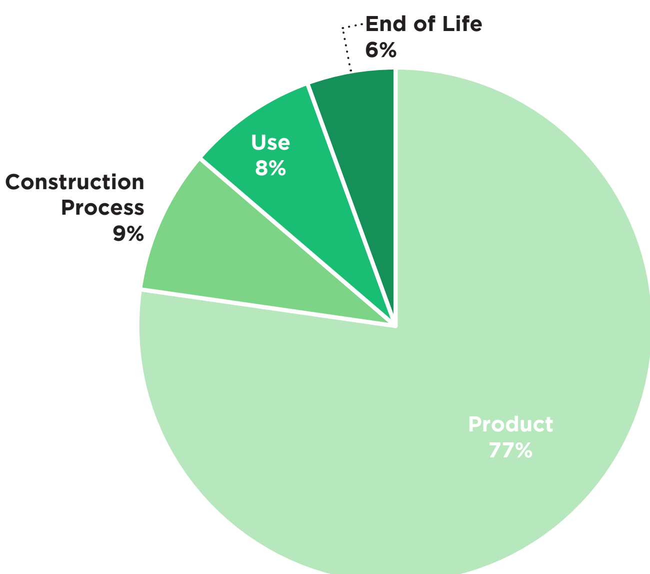
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
CONCRETE

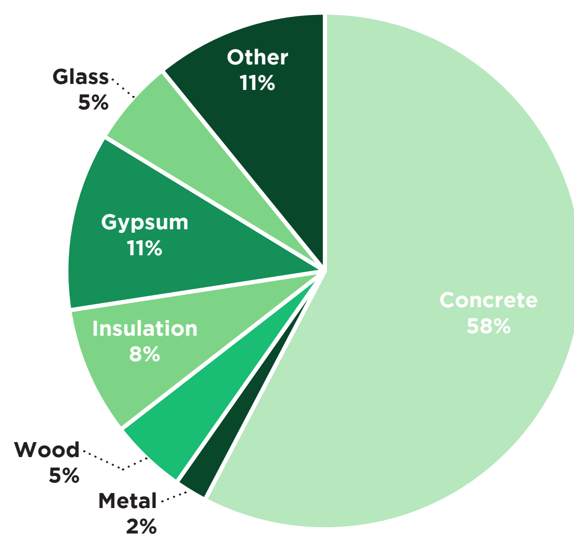




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

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EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT

SFU PARCEL 21

162
kg CO_2 eq./m²

ARCHITECT | **Local Practice Architecture + Design**
STRUCTURAL ENGINEER | **Associated Engineering**
YEAR COMPLETED | **Under Construction (2021)**
LOCATION | **SFU Burnaby Campus, BC**
USE | **Multi-unit residential**
GFA | **7,299 m²**
TOTAL STORIES | **6 / 4 / 1**
HEIGHT | **20.5 m / 17.1 m / 7.3 m**
PRIMARY STRUCTURE | **Wood-frame and concrete parkade**

The Parcel 21 complex, located in the SFU Burnaby Campus in BC, is a student residence with 90 affordable rental units and amenity spaces. The residence includes a four-storey and six-storey wood frame buildings on a concrete parkade, connected by a single-storey pavilion. The building is designed to Passive House standards and in terms of materials, this means that the building has a highly-insulated envelope, high-performance windows and thermal separation of canopies and other structures. Additionally, the building is designed for high seismicity with structural details that mitigate the effects of vertical shrinkage and preserve the continuity of thermal envelope for the residential area of the structure.

LCA PARAMETERS

PROJECT DATA SOURCE
Architectural BIM model

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Athena IE4B (Version 5.4.0101)

DATE OF ASSESSMENT
January 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls
Interior walls and doors
Roof

NOTABLE EXCLUSIONS
Exterior windows and doors
Interior finishes

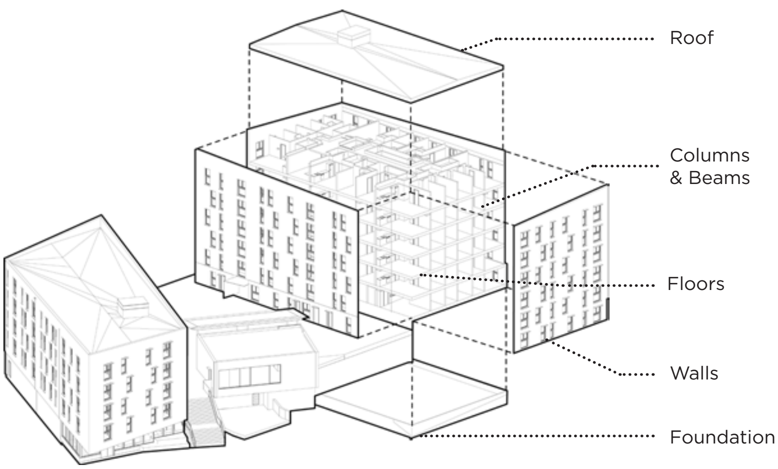
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4-A5)
Use (B2, B4), End of Life (C1-C2, C4)

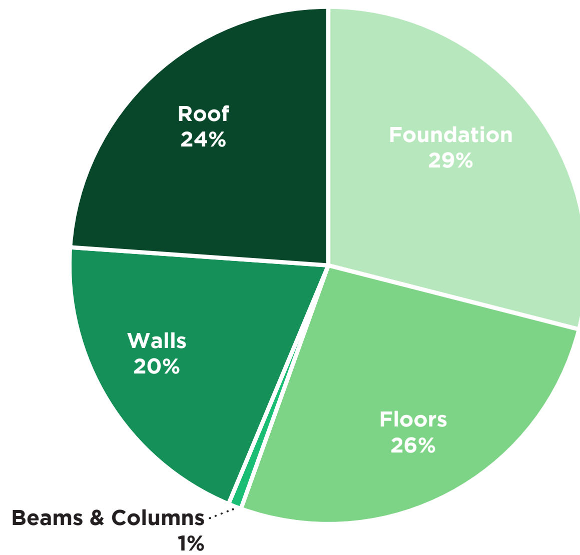
TOTAL GWP
1,184,348
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
FOUNDATIONS

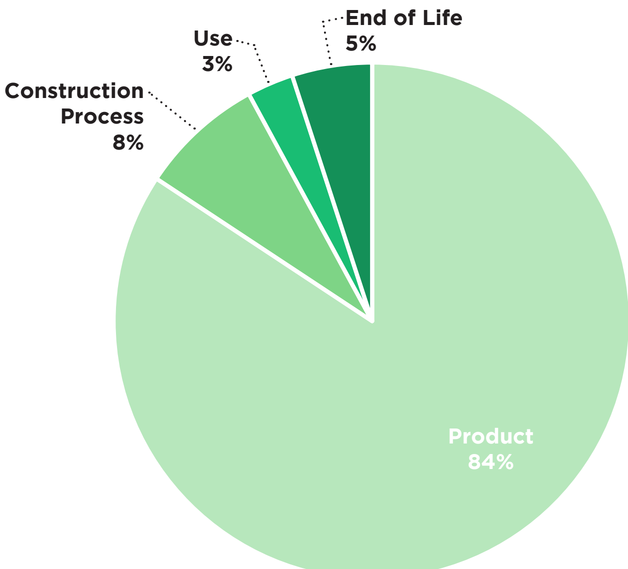
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
CONCRETE

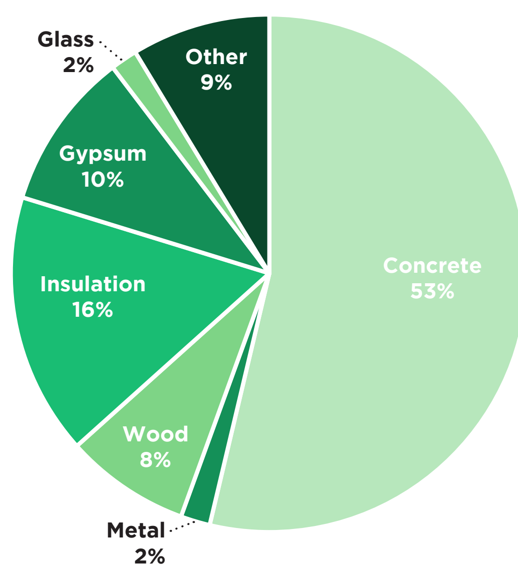




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

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784
kg CO_2 eq./m²

EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT
ATHENA IE4B

TRIUMF IAMI (A)

ARCHITECT | **Architecture 49**
STRUCTURAL ENGINEER | **Bush, Bohlman & Partners**
YEAR COMPLETED | **Under Construction**
LOCATION | **UBC Vancouver Campus, BC**
USE | **Institutional**
GFA | **3,575 m²**
TOTAL STORIES | **5**
HEIGHT | **21.8 m**
PRIMARY STRUCTURE | **Concrete and Steel**

The Institute for Advanced Medical Isotopes (IAMI), located on the TRIUMF campus at UBC Vancouver is a research facility that will be used to support next-generation research on medical isotopes and radiopharmaceuticals. The building will accommodate a new particle accelerator and integrated lab and office space. The concrete and steel frame building with five levels (two levels below grade) includes spaces like labs, technical rooms, change rooms, mechanical/electrical rooms and offices. The building design considered the building orientation, positioning of main entrances, strategic location of loading bays, noise generating equipment, air intake, labs and office spaces, and view corridors from adjacent facilities. As required by the UBC campus, the building, which is currently under construction, is targeting LEED Gold certification.

LCA PARAMETERS

PROJECT DATA SOURCE
Architectural and structural BIM models

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Athena IE4B (Version 5.4.0101)

DATE OF ASSESSMENT
February 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls, windows and doors
Interior walls, windows and doors
Roof

NOTABLE EXCLUSIONS
Suspended ceilings and interior finishes

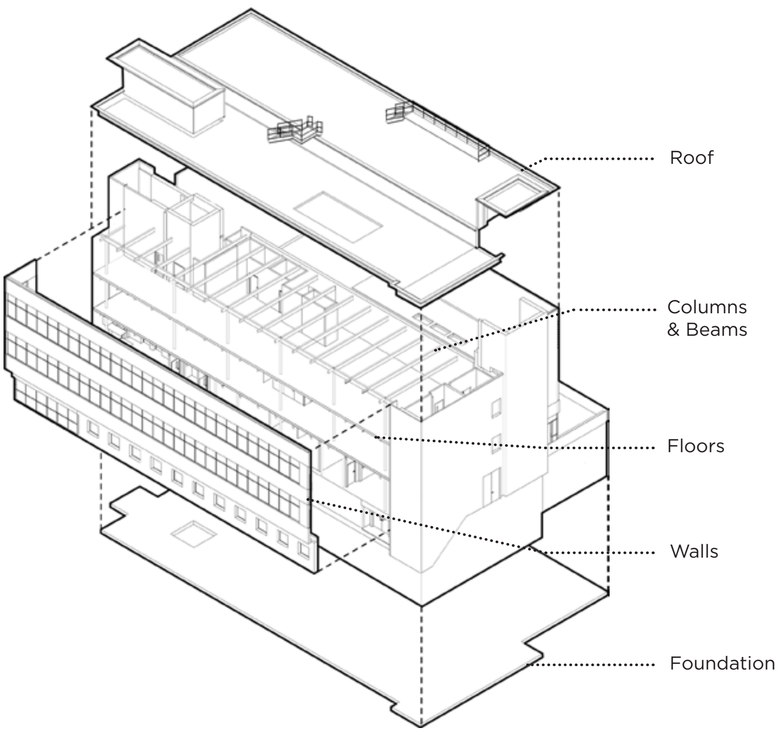
SYSTEM BOUNDARY (LIFE CYCLE STAGES)
Product (A1-A3), Construction Process (A4-A5)
Use (B2, B4), End of Life (C1-C2, C4)

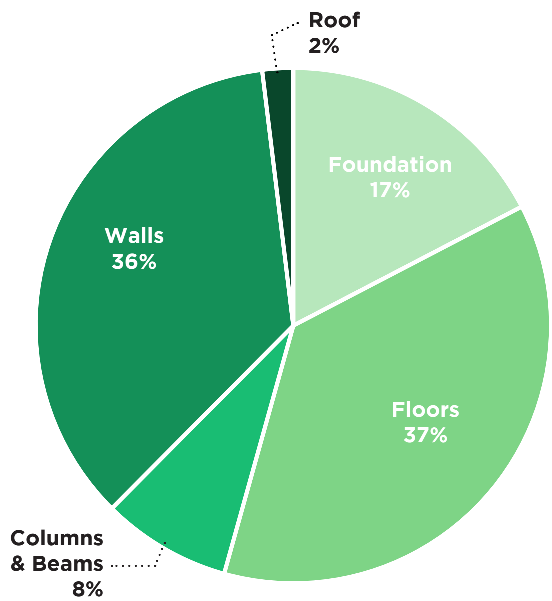
TOTAL GWP
2,804,584
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
FLOORS

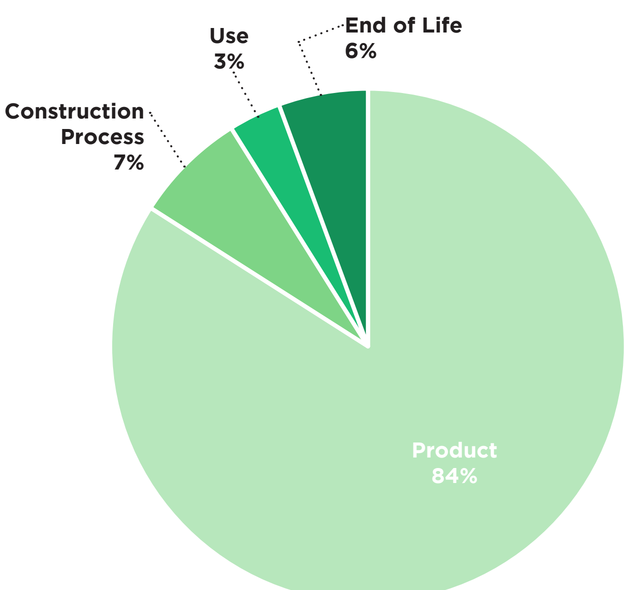
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
CONCRETE

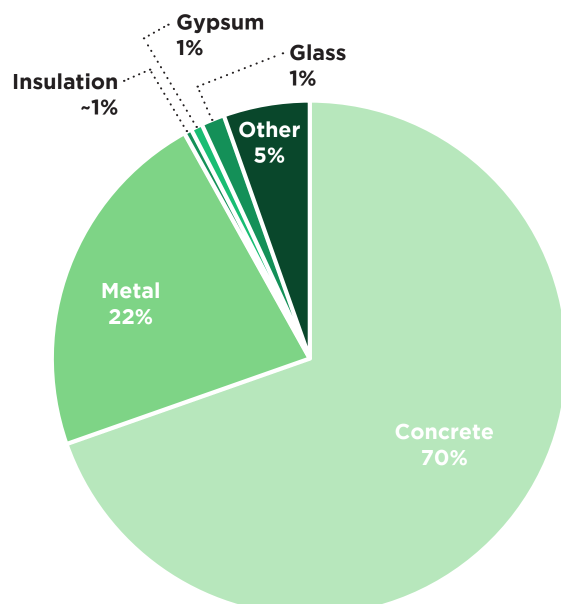




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

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1,047
kg CO_2 eq./m²

EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT
TALLY

TRIUMF IAMI (T)

ARCHITECT | **Architecture 49**
STRUCTURAL ENGINEER | **Bush, Bohlman & Partners**
YEAR COMPLETED | **Under Construction**
LOCATION | **UBC Vancouver Campus, BC**
USE | **Institutional**
GFA | **3,575 m²**
TOTAL STORIES | **5**
HEIGHT | **21.8 m**
PRIMARY STRUCTURE | **Concrete and Steel**

The Institute for Advanced Medical Isotopes (IAMI), located on the TRIUMF campus at UBC Vancouver is a research facility that will be used to support next-generation research on medical isotopes and radiopharmaceuticals. The building will accommodate a new particle accelerator and integrated lab and office space. The concrete and steel frame building with five levels (two levels below grade) includes spaces like labs, technical rooms, change rooms, mechanical/electrical rooms and offices. The building design considered the building orientation, positioning of main entrances, strategic location of loading bays, noise generating equipment, air intake, labs and office spaces, and view corridors from adjacent facilities. As required by the UBC campus, the building, which is currently under construction, is targeting LEED Gold certification.

LCA PARAMETERS

PROJECT DATA SOURCE
Architectural and structural BIM models

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Tally (Version 2020.06.09.01)

DATE OF ASSESSMENT
February 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls, windows and doors
Interior walls, windows and doors
Roof

NOTABLE EXCLUSIONS
Suspended ceilings and interior finishes

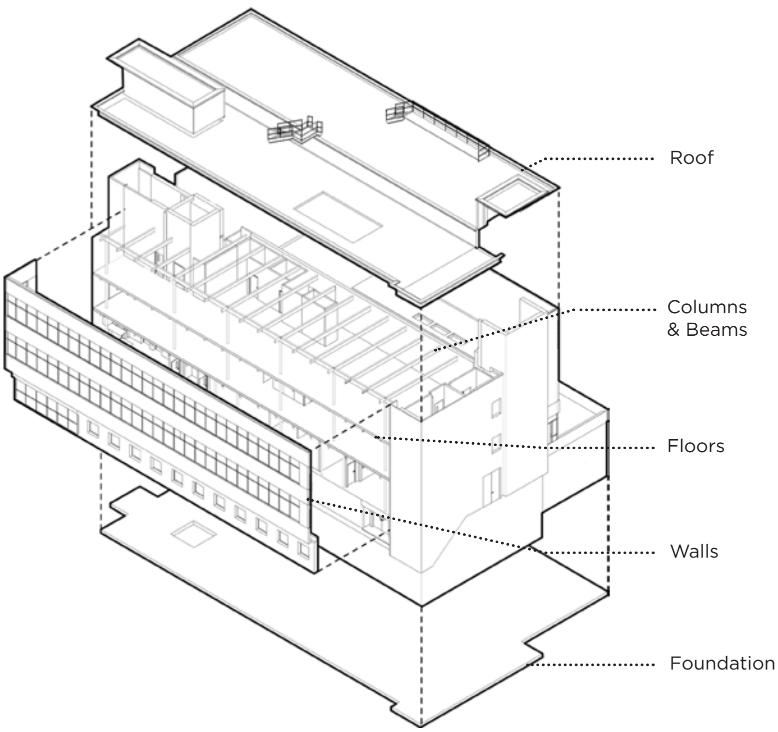
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4)
Use (B2-B5), End of Life (C2-C4)

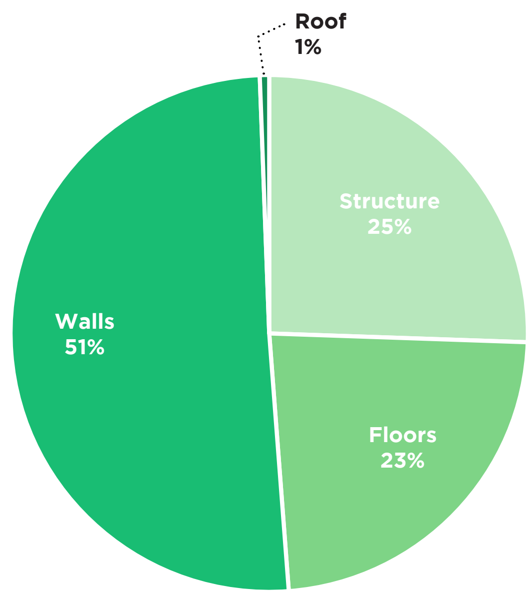
TOTAL GWP
3,744,552
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
WALLS

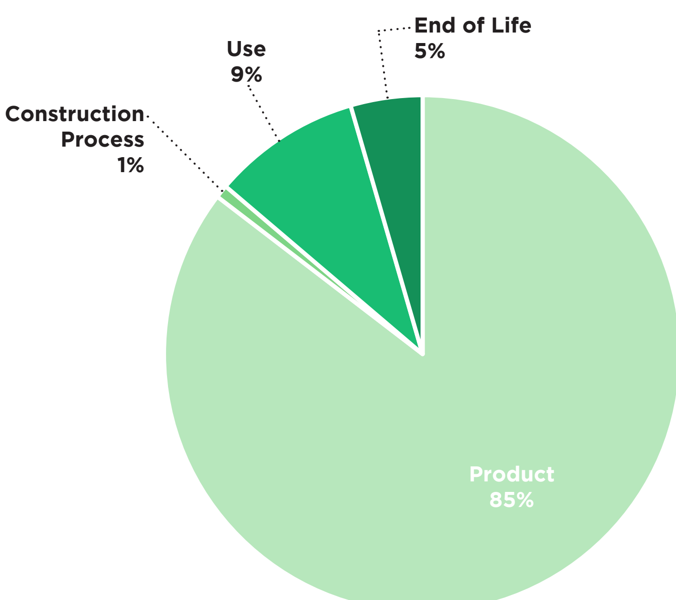
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
CONCRETE

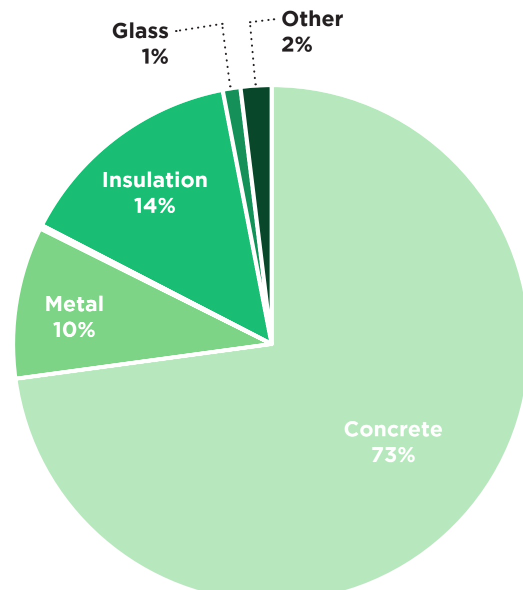




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

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198
kg CO_2 eq./m²

EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT
ATHENA IE4B

UBCO SKEENA (A)

ARCHITECT | **Public Design**
STRUCTURAL ENGINEER | **Bush, Bohlman & Partners**
YEAR COMPLETED | **2020**
LOCATION | **UBC Okanagan Campus, BC**
USE | **Student residence**
GFA | **6,744 m²**
TOTAL STORIES | **6**
HEIGHT | **20.6 m**
PRIMARY STRUCTURE | **Wood-frame and concrete**

The Skeena Residence, located at the UBC Okanagan Campus in Kelowna, BC is a student housing building with 220 beds and amenities including a lounge and study spaces, an activity room and laundry facilities. The new residence aims to support the growing demand of on-campus housing and focus on student life and services. The six storey has a concrete ground floor and wood-frame structure from second to sixth floor. The building design was driven by space and energy optimization through a repeating module of two bedrooms with shared bathroom. The building is targeted to achieve Passive House certification.

LCA PARAMETERS

PROJECT DATA SOURCE
BIM model

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Athena IE4B (Version 5.4.0101)

DATE OF ASSESSMENT
February 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls, windows and doors
Interior walls, windows, doors and ceilings
Roof

NOTABLE EXCLUSIONS
Interior finishes

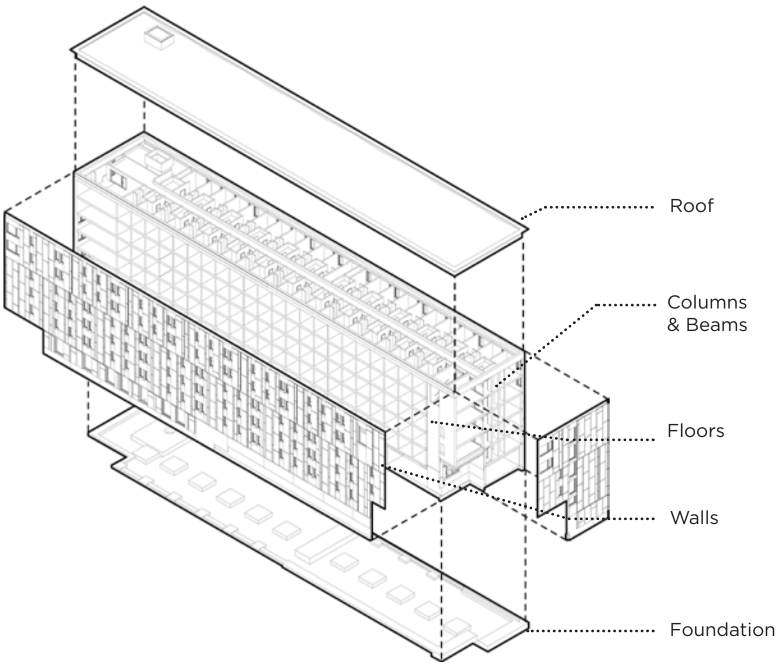
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4-A5)
Use (B2, B4), End of Life (C1-C2, C4)

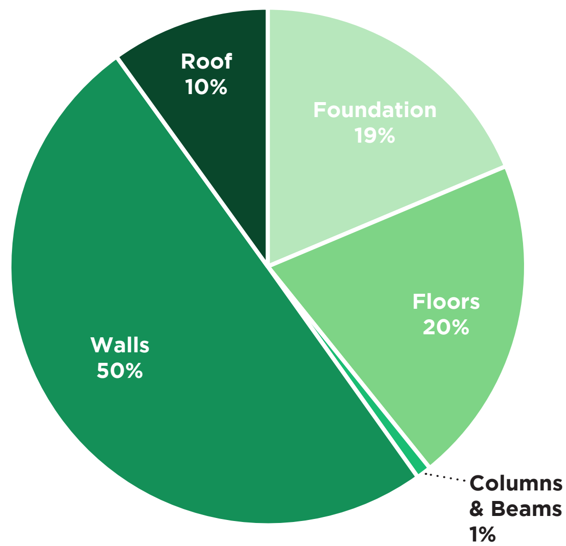
TOTAL GWP
1,338,625
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
WALLS

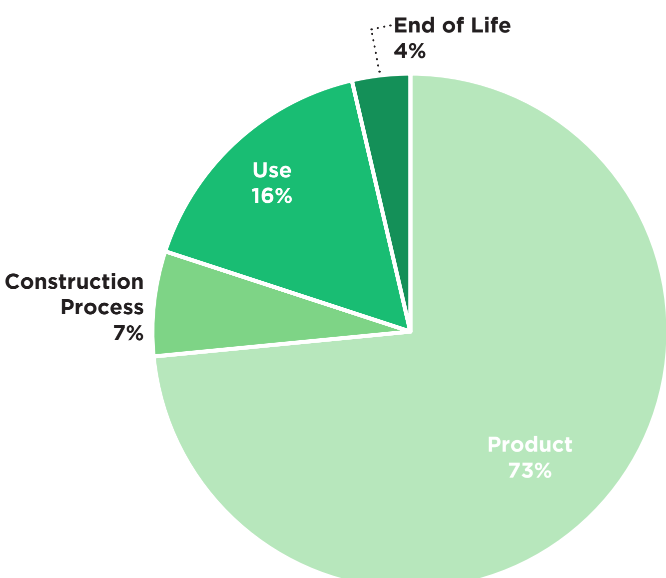
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
INSULATION

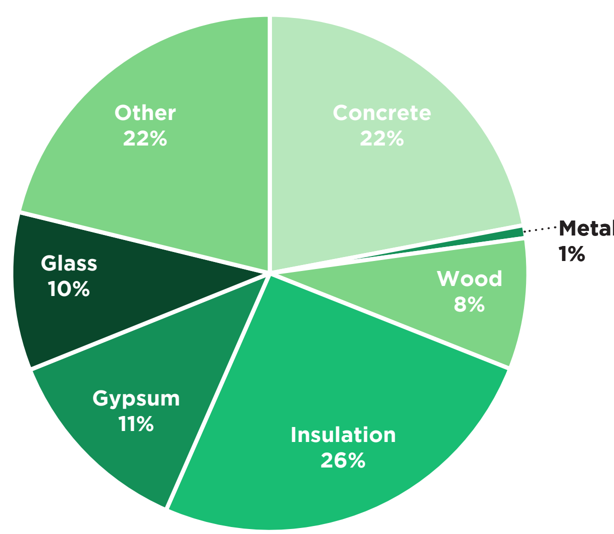




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

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730
kg CO_2 eq./m²

EMBODIED CARBON CALCULATOR THROUGH WHOLE-BUILDING LIFE CYCLE ASSESSMENT
TALLY

UBCO SKEENA (T)

ARCHITECT | **Public Design**
STRUCTURAL ENGINEER | **Bush, Bohlman & Partners**
YEAR COMPLETED | **2020**
LOCATION | **UBC Okanagan Campus, BC**
USE | **Student residence**
GFA | **6,744 m²**
TOTAL STORIES | **6**
HEIGHT | **20.6 m**
PRIMARY STRUCTURE | **Wood-frame and concrete**

The Skeena Residence, located at the UBC Okanagan Campus in Kelowna, BC is a student housing building with 220 beds and amenities including a lounge and study spaces, an activity room and laundry facilities. The new residence aims to support the growing demand of on-campus housing and focus on student life and services. The six storey has a concrete ground floor and wood-frame structure from second to sixth floor. The building design was driven by space and energy optimization through a repeating module of two bedrooms with shared bathroom. The building is targeted to achieve Passive House certification.

LCA PARAMETERS

PROJECT DATA SOURCE
BIM model

PROJECT PHASE
Design development complete

LCA STUDY PERIOD
60 years

TOOL
Tally (Version 2020.06.09.01)

DATE OF ASSESSMENT
February 2021

LCA SCOPE

OBJECT OF ASSESSMENT
Foundation and slab-on-grade
Floors (incl. stairs)
Exterior walls, windows and doors
Interior walls, windows, doors and ceilings
Roof

NOTABLE EXCLUSIONS
Interior finishes

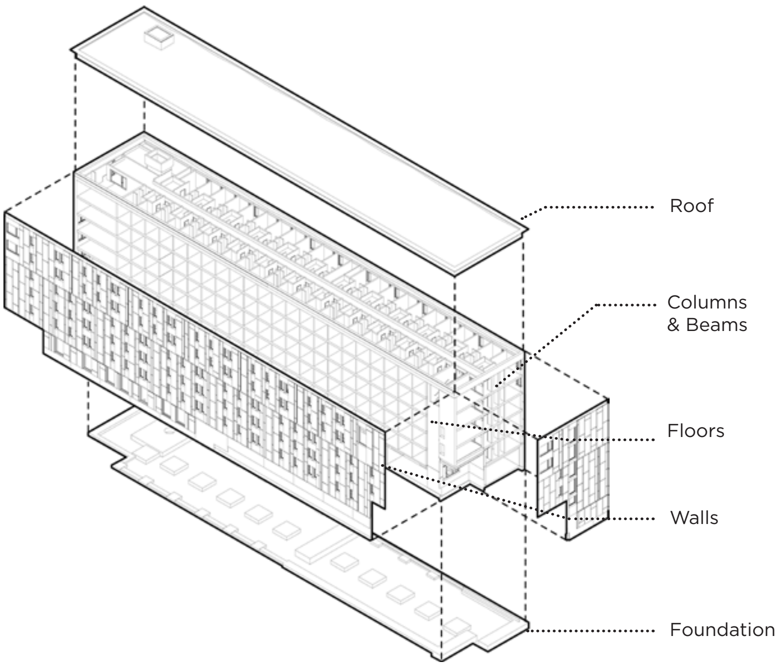
SYSTEM BOUNDARY (LIFE CYCLE MODULE)
Product (A1-A3), Construction Process (A4)
Use (B2-B5), End of Life (C2-C4)

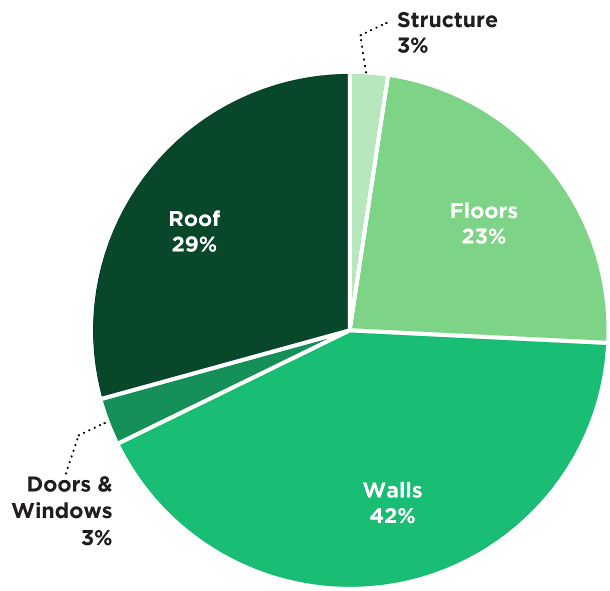
TOTAL GWP
4,923,868
kg CO_2 eq

HIGHEST IMPACT
BUILDING ASSEMBLY
WALLS

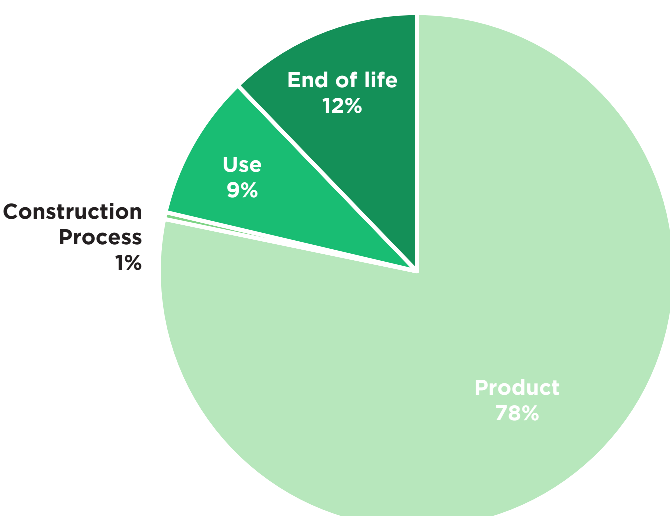
HIGHEST IMPACT
LIFE CYCLE MODULE
A - PRODUCT

HIGHEST IMPACT
BUILDING MATERIAL
INSULATION

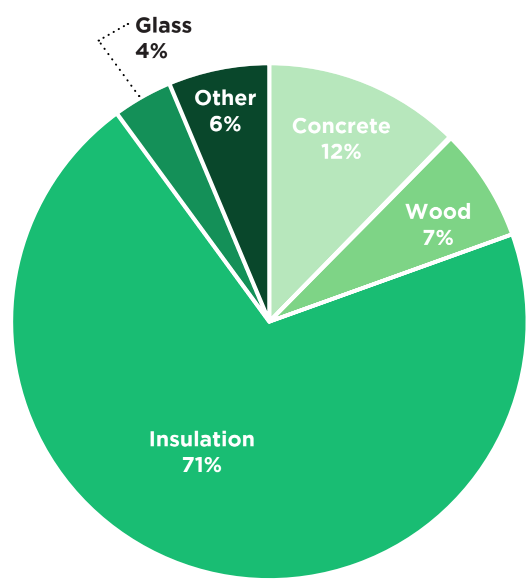




GWP BY BUILDING ELEMENT



GWP BY LIFE CYCLE STAGE



GWP BY BUILDING MATERIAL

This assessment was conducted for research purposes and should not be used for reporting or policy compliance purposes. Results from different assessments may not be comparable to each other; the highest impact categories noted above represent the most prominent assembly, life cycle stage and material for each assessment, which indicate potential areas for improvement in embodied carbon emissions.

4.4 Results summary

The LCA results were limited to embodied carbon only, reported in the GWP environmental impact category. All the assessment results were normalized by GFA, which we recalculated for each building to ensure that we included all the areas of the building with materials being quantified (some project GFA calculations exclude parkade or unheated spaces). Results are reported in kg of CO_2 equivalent per m^2.

The results have a wide range of variability because of the different building typologies, uses, designs and material choices, as well as different project data sources and LCA tools. Generally, wood-frame buildings had the lowest total building GWP impacts. Carrington View, a wood-frame multi-unit residential building, has an estimated impact of 121 kg CO_2 eq./m^2. SFU Parcel 21 and UBCO Skeena, both wood-frame student residences, were also on the lower side of the spectrum, with impacts of 162 kg CO_2 eq./m^2 and 198 kg CO_2 eq./m^2 using Athena IE4B, respectively. In addition, 2150 Keith Drive, a mass timber hybrid office building, assessed using Tally, was estimated to have an embodied carbon of 227 kg CO_2 eq./m^2. Even though the main component of this building's structure is mass timber, wood as a material only accounted for 21% of the total embodied carbon, unlike concrete (incl. steel reinforcement) which accounted for more than half of the total building impacts at 56%.

The buildings with a concrete structure were estimated to have a higher embodied carbon footprint than the wood frame buildings. 825 Pacific and Brock Commons Phase 2 had a similar impact at 430 kg CO_2 eq./m^2 and 450 kg CO_2 eq./m^2 respectively. TRIUMF IAMI, being the most material-intensive building with a concrete and steel structure, was the highest at 784 kg CO_2 eq./m^2 assessed with Athena IE4B and 1,047 kg CO_2 eq./m^2 assessed with Tally.

One of the notable results is the differences between the results for UBCO Skeena and TRIUMF IAMI using Athena IE4B and Tally. UBCO Skeena had an estimated embodied carbon of almost 200 kg CO_2 eq./m^2 with the Athena IE4B, and 730 kg CO_2 eq./m^2 with Tally. This discrepancy can be largely attributed to the impacts calculated for the insulation materials. Although the quantities for these materials were the same for both assessments, the database in Tally estimated the impacts of insulation as approximately six times higher than Athena's database. Since this building was designed to be Passive House certified, the amount of insulation is much higher than in a conventional building, exacerbating the differences in the two tools' databases. TRIUMF IAMI was estimated to have an embodied carbon of 784 kg CO_2 eq./m^2 with Athena IE4B and 1,047 kg CO_2 eq./m^2 with Tally. While this also illustrates the differences in the tools' databases, in this case, the difference was more evenly distributed among the main structural materials, concrete and metals (incl. structural steel), as well as insulation.

The results of the assessment were broken down by life cycle stage, building element and material. As expected, in all of the assessments, the highest life cycle stage by far was Product (A1-A3). The production stage is recognized as the most emission-intensive in building development. The building element that contributes the most to the embodied carbon of a building varied between floors and walls, although the components included in these classifications might not be consistent across tools. Each tool has its own classification system so the breakdown that was used to show results by building element was based on the outputs of the tool, therefore they might be different among assessments. The material results varied the most widely and were the most influenced by the building design. Across the buildings, concrete (incl. rebar), insulation and metals were consistently high impact materials. Gypsum was also significant in some buildings. Wood was consistently low impact, even in the buildings where it is used as the primary structural material, ranging from 5% - 8% in all wood-frame buildings and 23% for the mass timber hybrid building (2150 Keith Drive).

5

ANALYSIS AND DISCUSSION

5.1 Proposed BoM generation methodology

In Phase 1 of the Pilot, the research team conducted nine LCAs on three buildings with different types of data sources and tested different LCA software tools. This was done to explore the process of conducting LCAs and to analyze the factors that may affect consistency, reliability and variability of results. Five main factors were identified:

- Availability of project data sources that contain information on the building materials and their quantities.
- Means of determining which building components and materials should be included in the assessment (object of assessment).
- Means of determining which life cycle stages are included in the assessment (the system boundary).
- Methods of generating a BoM to categorize and quantify the building's specific materials.
- Selection of the embodied carbon software/web tools that calculate the embodied carbon emissions of the materials and products.

Based on these findings, in Phase 2 we started by defining a comprehensive list of parameters that need to be determined before conducting an LCA, as well as a set of steps to create a detailed BoM of a building that can then be used to conduct the assessment. This BoM generation methodology is based on the phases of LCA outlined in the ISO 14040 standard. The team also identified the different types of BoM created throughout the process as the project data is manipulated into a format that can be assessed using an LCA software tool.

The assessment parameters that need to be determined by the practitioner prior to conducting an LCA are listed below. These apply whether the assessment is a WBLCA, a partial LCA or an embodied carbon calculation.

Parameters:

- Goal of the LCA
- Scope of the LCA, which consists of:
  - Object of assessment: building components to be assessed
  - System boundary: life cycle stages included in the LCA
  - Reference study period: time period over which the building is being assessed
- Available project data sources, which can be classified by the level of accuracy as:
  - Primary, from purchase orders and receipts
  - Project-specific, from project drawings, BIM model and cost estimates
  - Product-specific, from EPDs
  - Secondary, from industry averages

- Appropriate assessment tool, which should be chosen based on the:
  - System boundary it can assess, such as only production or the full building life cycle
  - Input methods it allows, such as direct input of BoM or BIM integration
  - Databases used by the tool to map the materials and assess their environmental impacts
  - Format and level of granularity of the results

We have found that it is important to determine the parameters for the LCA before conducting the assessment and even before starting to collect project data. Without a well-established set of parameters, the goal of the LCA is likely to be unaccomplished and the LCA process will likely be both challenging and inconsistent. Section 2 of this report defines each parameter in more detail and highlights the variability in the LCA results based on these parameters. Parameters should be determined by the goal of the LCA and provide a framework for decisions made throughout the LCA process. If the purpose of the LCA is to inform design decisions, these parameters can be set by the project team. However, if the purpose of the LCA is to demonstrate compliance with a performance target or to collect information to establish policy benchmarks, the parameters should be clearly articulated by the regulation or standard to provide direction to project teams and improve consistency between assessments.

Once the assessment parameters are defined, the process to create a BoM for input into an LCA tool can be outlined in these four steps:

- **STEP 1: Building data extraction** – Material quantities are extracted from the project data source. Assemblies within the object of assessment are organized in Excel, creating the project's Raw Data.

- **STEP 2: Quantity calculations** – Calculations are performed to convert the material quantities from the Raw Data into commonly used units, then consolidated into the Building BoM.

- **STEP 3: Material mapping** – Materials from the Building BoM are matched to the closest materials available in the LCA tool's database and assigned to categories based on the tool's classification system, creating the Modified BoM.

- **STEP 4: Input into LCA tool** – The Modified BoM is input into the tool. The LCA tool may make additional adjustments based on its internal algorithms or require additional information from the practitioner.

Once the LCA tool has the BoM information, it assesses the environmental impacts of these materials and the processes they go through throughout the chosen life cycle stages (e.g. production, construction, maintenance, replacement, and disposal or recycling). The environmental impact results and the corresponding Output BoM are exported from the tool. The results should be reviewed for accuracy and will need to be interpreted by the practitioner to inform design or policy decisions. However, the review and interpretation of results are beyond the scope of this current Pilot.

During Phase 2 of the Pilot, we tested the parameters and the BoM generation methodology by conducting LCAs on seven buildings, ranging from multi-unit residential and student residences, to commercial and institutional typologies. Similar to Phase 1, we used different data sources based on the availability of project information, as well as different LCA software tools to conduct the assessments. An overview of these assessments and results are described in Section 5 of this report. We found that the methodology worked well with the range of assessments conducted in Phase 2.

While the four steps outlined above generally occur in the stated order, we found that specific tasks in each step can overlap and vary depending on the project data sources, quality of information, and LCA tool. However, the basic structure of the process is the same for all assessments: first, the team established the LCA goal and the rest of the parameters (which were generally consistent for all our assessment); next, the team sourced, extracted, calculated and organized material quantities and characteristics, either manually or through the LCA tool software; and lastly, the team mapped the project material data to the available materials in the tool and input the data into the LCA tool to be assessed.

We have observed that generally, the last part of the proces, when the data is mapped and input into the tool tends to be the most emphasized when discussing LCAs. These are also the steps that LCA tool developers have focused on making easy and accessible to practitioners by improving the user interfaces. However, there is a significant amount of work that needs to take place to extract the project data, calculate material quantities and prepare it for input into the LCA tool. We observed that many assumptions and decisions are made during these earlier processes in Steps 1 and 2, which can influence the accuracy and usability of the LCA results. There is still very little guidance for practitioners on how to perform and document these processes. The methodology developed through the Pilot, and outlined in Section 3, is an attempt to address this lack of guidance. Towards that end, we are publishing the methodology sections of this report as a white paper, to encourage discussion and debate to improve the processes of conducting LCAs.

5.2 Impact of LCA scope on inputs and outputs

5.2.1 Object of assessment

Phase 2 of the Pilot consisted of 9 assessments on 7 different buildings with very different structures (wood frame, mass timber and concrete) and typologies (residential, commercial and institutional). As part of the methodology for this phase, we attempted to keep the object of assessment consistent for all projects, subject to data limitations. The object of assessment was also meant to be as comprehensive as the data sources allowed, and generally included substructure, shell and interiors but excluding finishes, services, equipment and site work. We use the UniFormat classification system to categorize the building assemblies and materials and organize the Building BoM. The general object of assessment for all LCAs is detailed in Figure 8, organized in UniFormat.

The Modified BoM is the Building BoM mapped to the materials in the LCA tool database and organized based on the tool's internal classification system. Because it is based on the Building BoM, the overall object of assessment is the same but the categorization of building elements and materials within it may be slightly different. Since each tool has its own internal classification system, analysis of the Modified BoM is not feasible between assessments using different tools.

To better understand the impact that the object of assessment may have on the estimated embodied carbon emissions for each building, we calculated the percentage contribution of each category to the total embodied carbon emissions. The results from this analysis are illustrated in Figure 9, Figure 10 and Figure 11. The assessments were divided into three different graphs according to the tool that was used to perform the assessment and the total building impacts are broken down by percentage into the different building elements according to the tools' classification systems.

Level 1		Level 2		Object of assessment
Major group elements		Group elements		
A	Substructure	A10	Foundations	X
		A20	Subgrade enclosures	X
		A40	Slabs-on-grade	X
		A60	Water and gas mitigation	-
		A90	Substructure related activities	-
B	Shell	B10	Superstructure (Floors, roof, stairs)	X
		B20	Exterior vertical enclosures (Exterior walls, windows, doors)	X
		B30	Exterior horizontal enclosures (Roofing)	X
C	Interiors	C10	Interior construction (Partitions, ceilings)	X
		C20	Interior finishes	-
D	Services			-
E	Equipmnent and Furnishings			-
F	Special Construction and Demolition			-
G	Sitework			-

Figure 8: Object of assessment organized by UniFormat classification system

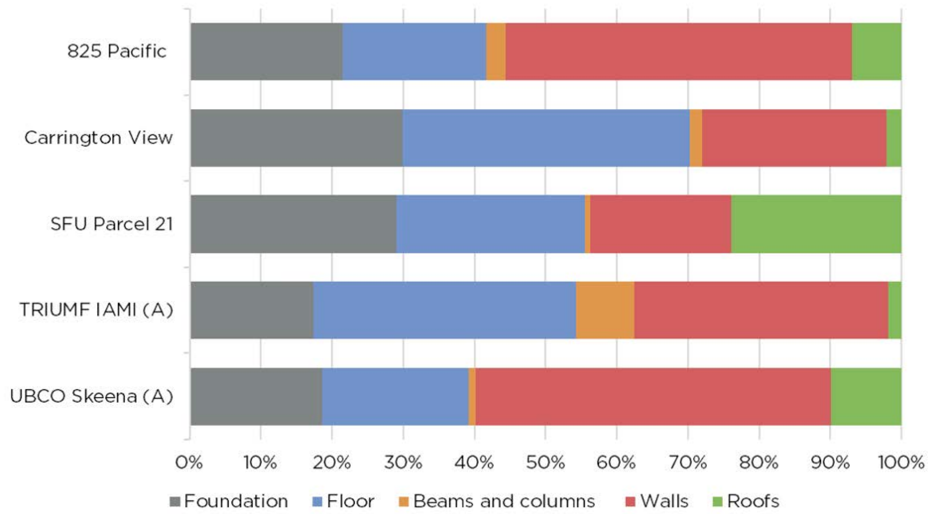


Figure 9: Proportion of GWP by building element (modules A-C) for Athena IE4B assessments

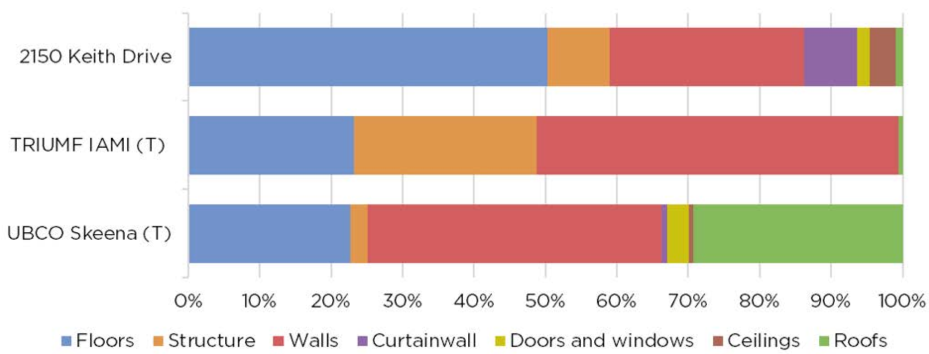


Figure 10: Proportion of GWP by building element (modules A-C) for Tally assessments

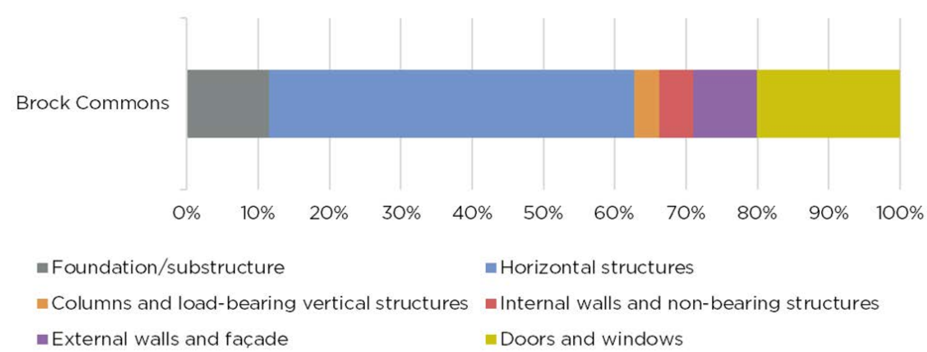


Figure 11: Proportion of GWP by building element (modules A-C) for One Click LCA assessments

Generally, as noted above, the object of assessment for all of the buildings encompassed the structure (including foundations), building envelopes and roofs, and interior partitions. We included window and door assemblies, but excluded mechanical and electrical systems and finishes. Across the majority of assessments, walls, roofs, and structural elements (e.g. beams and columns) make up a significant portion of the embodied carbon impacts. From this breakdown, we see that the building's envelope and structure are important elements to capture as they comprise a majority of the embodied carbon impacts. On the other hand, from the tools that provide more breakdown, such as Tally, we can observe that elements like doors, windows and ceilings do not represent a significant portion of the overall emissions, although they are significant in the One Click LCA assessment of Brock Commons.

Interior walls are included within the 'Walls' category for most of the assessments (except for One Click LCA which divides external walls and facades from internal walls and non-bearing structures). Most likely, structural walls will contribute more to the impacts of a building than interior partitions. Nevertheless, we consider it important to capture all the walls if possible. All of our assessments exclude finishes from the object of assessment because of calculation difficulties and data limitations (finishes are not usually included in a BIM model). For this reason, we are not able to assess the impact that finishes would have on the total building emissions.

These three graphs also illustrated one of the fundamental differences in LCA tools, how the building components within the object of assessment are classified. Athena IE4B has five broad categories: foundation, floors, beams/columns, walls and roofs. Tally uses the categories specified in the BIM model, which may be different for each building project. One Click LCA displayed the results using six categories: foundations/substructures, horizontal elements (floor slabs/ceilings/beams/roof decks/roof), vertical structural elements (e.g. columns), vertical non-structural elements (e.g. internal walls), external walls/facades, and windows/doors. Depending on the chosen tool, the assessment categories include different building elements and assemblies. In trying to assess the impacts from walls, for example, doors and windows would be included in an Athena IE4B assessment, which would increase the impacts associated with that category, but would be broken out on their own in Tally or One Click LCA. Tally also distinguishes between different wall types as specified in the BIM model, while One Click LCA distinguishes between internal and external walls, which would further break down the impacts from walls into multiple categories.

Different levels of detail and the break out of specific elements may be more or less valuable for different types of assessment, again depending on the goal of the LCA and its scope. This is why setting these parameters ahead of conducting an assessment is so important, and ensuring that the object of assessment and tool are appropriate for the purposes of the LCA.

Variation of GFA calculation when normalizing results by m²

In order to report LCA results by unit of area (e.g. kg CO_2 eq./m²), the total impacts are divided by the gross floor area (GFA) of the building. The GFA used in the LCA assessment needs to align with the object of assessment. For example, often GFA for rezoning or other purposes will exclude parkades or unheated spaces, however, if the materials in those assemblies are part of the object of assessment then the spaces need to be included in the LCA GFA. This means that the GFA for an LCA may be different than a GFA for other purposes. For the Pilot, the research team calculated GFA for all the buildings to match the object of assessment. Figure 12 compares the GFA noted in project documents with the GFA calculated by the research team.

The GFAs calculated by the Pilot's research team were based on the Canadian Institute for Quantity Surveyors (CIQS) method for calculating gross floor area — as recommended in the upcoming Guidelines for Whole-building LCA (National Research Council Canada, 2021). Our GFA calculations were relatively consistent with the GFA values taken from the project teams' documents. The most significant variation was for 825 Pacific which had a 20% difference. In this case, the GFA in the project drawings excludes the building areas below grade, which include a basement that houses mechanical and electrical rooms, garbage room, bike storage, among others. However, the materials in the underground levels were included in the LCA object of assessment, therefore these areas should be included in the GFA used for LCA purposes. Other variations are likely due to differences in including components like parking or double-height spaces, measuring to the interior, midpoint or exterior of walls, and similar decisions. It is important to document these decisions to understand how they can influence the results.

This comparison shows the potential range of variation in GFA measurements. If policymakers request environmental impact results by building area (e.g. kg CO_2 eq./m²), they should provide clear guidelines or require an existing established method of how to calculate GFA for the LCA. Having a clear set of rules would help standardize the practice of reporting LCA results.

Building	From Project Teams		Calculated by Pilot's Research Team		Difference (%)
	GFA (m²)	Data Source	GFA (m²)	Data Source	
2150 Keith Drive	-	Unable to find from Architectural IFB Project Drawings	24,555	IFB Architectural Drawing Set	-
825 Pacific	2,220	Architectural IFC Drawings "Gross GFA" total from Building Area table (A0.01)	2,740	IFC Architectural Drawing Set	20%
Brock Commons	18,090	Architectural Revit Model Pre-made Gross Building Area Schedule	19,543	IFT Architectural Drawing Set	8%
Carrington View	7,740	Class C Cost Estimate (Parkade + Apartment)	7,729	IFC Architectural Drawing Set	0.1%
SFU Parcel 21	7,299	Architectural Revit Model "Total GFA" Material Schedule	7,606	IFC Architectural Drawing Set	4%
TRIUMF IAMI	3,392	DP Architectural Drawings (resubmission) Site Plan – Project Statistics Table	3,575	DP Architectural Drawing Set	5%
UBCO Skeena	6,749	Architectural Revit Model Pre-made Gross Building Area Schedule	6,744	IFC Architectural Drawing Set	0.1%

Figure 12: Variation of GFA from project documents and re-calculated for LCA

5.2.2 Life cycle stages

The life cycle stages used by most LCA tools are part of a standardized classification system that categorizes the building life cycle into stages and modules: product stage (modules A1-A3), construction process stage (modules A4-A5), use stage (modules B1-B5 plus B6-B7 if applicable) and end of life stage (modules C1-C4). Some tools also calculate benefits and loads beyond the system boundary stage (module D). But even though the classification system is the same, tools have different life cycle scopes and may account for each module differently. For example, some tools only calculate certain modules within each life cycle stage and exclude the others for lack of data. Other tools only calculate the impacts in certain modules if additional information beyond just the material quantities is provided by the practitioner.

To assess the impact that each life cycle stage has on the estimated embodied carbon emissions for each building, we calculated the percentage contribution of each stage compared to the total emissions. The results from this analysis are illustrated in Figure 13. This graph only includes impacts within the life cycle of the building, i.e. product, construction, use and end of life (modules A-C). The tools used in each assessment are indicated by the initials in parenthesis after the building: (A) is Athena IE4B, (T) is Tally and (1C) is One Click LCA.

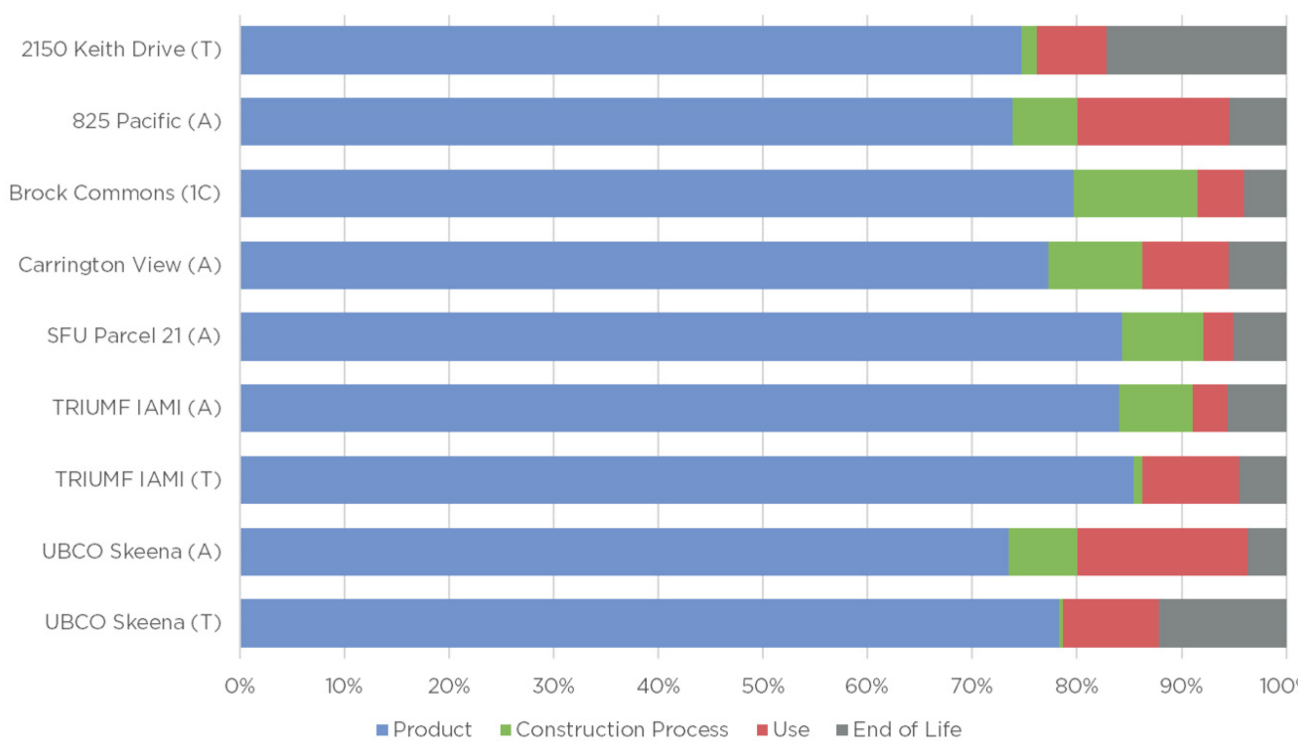


Figure 13: Proportion of GWP by life cycle stage (modules A-C) for all assessments

From Figure 13, we can observe that the product stage is by far the largest contributor to the overall embodied carbon emissions of all buildings, and ranges from 73% - 85% of the total GWP impact for these projects. The rest of the stages vary by assessment: construction stage impacts range from 0.4% - 12%, use stage impacts from 3% - 16%, and end of life stage impacts from 4% - 17%.

It is expected that every assessment would have a different breakdown due to the particularities of each building design and materials. Variations of the product stage between buildings assessed with two different tools are due to the underlying material data used within each tool. Variations in the other life cycle stages (construction process, use and end of life stages) can be attributed to differences in LCI/scenario data and life cycle scope in each tool. However, we are unable to explain these discrepancies in more detail since the tool outputs do not provide more breakdown in the results.

The product stage is the biggest contributor in all cases due to the emissions intensity of current material extraction and manufacturing activities. This impact also occurs in the present and immediately contributes to our current climate change emergency (as opposed to stages like use and end of life which span several decades in the future). This is the reason that many embodied carbon calculators focus on the product stage. However, the impacts from the other three categories still account for a significant amount of emissions, 15% - 27%, and should be included in the analysis to ensure that future improvements are not sacrificed for immediate gains. As climate change becomes more critical in the coming decades, future impacts of current design decisions are likely to become more problematic.

The variations amongst the assessments, including the variations in assessments of the same building through different tools, illustrate one of the challenges with conducting LCA for benchmarking and performance targets: the use of different tools and databases can influence the results. Because the tools rely on their own internal algorithms and draw from different LCI databases, it's difficult to determine why specific variations happen. For example, we conducted two assessments for the TRIUMF IAMI building using the same object of assessment and project data sources, but two different tools: Athena IE4B and Tally. When assessed using Tally, the impacts from the construction life cycle stage are quite small, while the use stage impacts are much larger. When assessed using Athena IE4B, however, the impacts from construction and end of life stages are more significant and the impacts from the use stage are lessened. This may be in part because Tally doesn't account for construction installation impacts (module A5) automatically and extra information is needed (which in this case we didn't include due to lack of data), whereas Athena IE4B calculates this module automatically with LCI and scenario data within their database.

5.2.3 Reference study period

The reference study period is the period over which the building is being assessed. This period usually, but not always, corresponds to the required service life of the building. For Phase 2 of the Pilot, we chose 60 years as the reference study period for all the buildings, since not all projects provided information on their required service life and 60 years is often standard for residential developments (which were the majority of the buildings). UBC buildings have a required service life of 100 years, but for the purposes of this Pilot, we used 60 years to be consistent across projects.

To assess the impact that changing the reference study period has on the estimated embodied carbon emissions for each building, we compared the total emissions for some of the assessments using a reference study period of 60 years and 100 years. The results from this analysis are illustrated in Figure 14. The tools used in each assessment are indicated by the initial in parenthesis after the building: (A) is Athena IE4B, (T) is Tally and (1C) is One Click LCA.

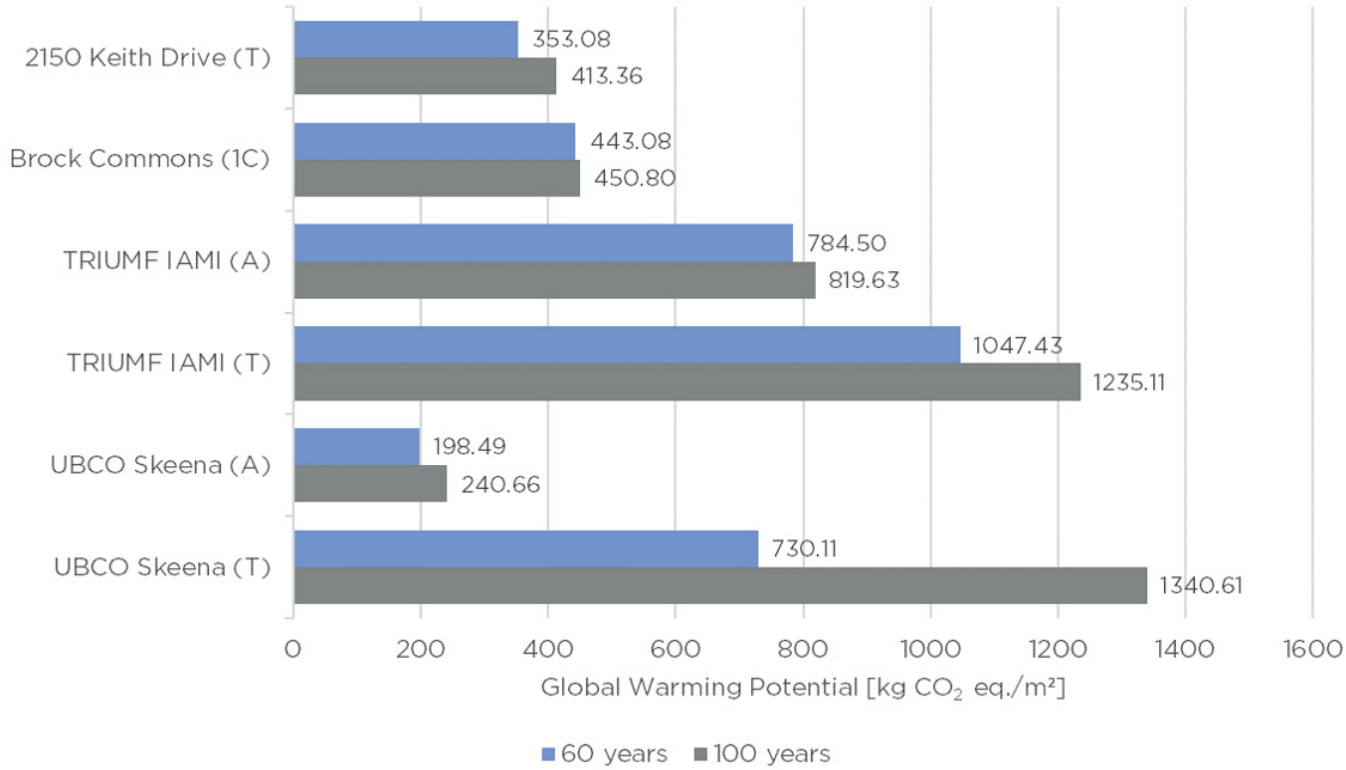


Figure 14: Total GWP impacts for 60-year and 100-year reference study periods for six assessments

Across all these assessments, the 100-year reference study period led to an expected increase in the embodied carbon emissions. The assessments conducted in Athena IE4B and One Click LCA have a similar result from both study periods, with a difference of 4% - 19% and 2%, respectively. However, the differences in the reference study period are much more significant for the assessments using Tally: 16% for TRIUMF IAMI, 16% for 2150 Keith Drive and 59% for UBCO Skeena.

This analysis shows that the reference study period does impact the results of an embodied carbon assessment, but that the variation may be relatively minor. This is partially due to the fact that the GWP impacts in the use stage (the one most influenced by the study period or service life due to material replacement cycles) tend to be minimal compared to other stages, such as product. Product, construction and end of life stages would generally not be influenced by an extended study period. However, it is important to consider both the upfront impact of material production as well as their longevity and replacement frequency when looking at overall embodied carbon impacts.

This analysis also illustrates variations in how the different LCA tools account for the reference study period and how they weigh the impacts from different life cycle stages. The differences between the GWP impacts from a 60-year and 100-year study period for UBCO Skeena in Athena IE4B and Tally are the most prominent and show the extent of variations in the tool's databases. In the UBCO Skeena Tally assessment, an increase of 40 years to the study period caused an increase of over half to the GWP Impacts. We, therefore, broke down the result for the UBCO Skeena Tally assessment by materials to try to understand the cause of such a big difference, shown in Figure 15.

The most significant contributor of GWP impacts in both reference study periods and of the substantial difference between the two is insulation. UBCO Skeena is designed to be Passive House Certified, which targets very low operational emissions throughout the use stage of the building. To achieve this, a substantial amount of insulation is needed for the building enclosure to act as an efficient barrier to the outside temperatures. The greater GWP contribution in the 100-year assessment could be due to an increased number of replacement cycles for the large volume of insulation. Tally's database may also include other assumptions around maintenance or disposal that could increase the impacts, but it is hard to pinpoint the exact reason from the tool's outputs.

There are also greater contributions from materials including metal, wood and gypsum board in the 100-year assessment, although these are small in comparison to the insulation. Structural materials such as concrete and steel reinforcement are identical in the two assessments due to the assumption that building structures are not replaced during the building service life and require little maintenance. From the analysis, we can observe that it is important to select a reasonable study period to make sure the appropriate maintenance and replacement effects in the use stage are included in the assessment.

The various analyses from section 6.2 illustrate the uncertainty inherent within building life cycle assessments and the importance of understanding the factors that influence a given tool's results. They also highlight the importance of interpreting the LCA results as mentioned in section 4. Practitioners should dig into results that seem out of the expected range and review the inputs and parameters to find possible causes for the discrepancy. Sometimes these unexpected results are not necessarily wrong but might benefit from interpretation from the practitioner as well.

In addition, when establishing LCA guidelines for benchmarking or to demonstrate achievement of performance targets, policymakers should specify these LCA parameters (i.e. object of assessment, system boundary and reference study period), but also include information on preferred tools to improve consistency between different projects. Alternatively, if policymakers wish to establish GWP performance targets, and if they wish to keep the choice of tool open, then they need to establish specific performance targets for each tool.

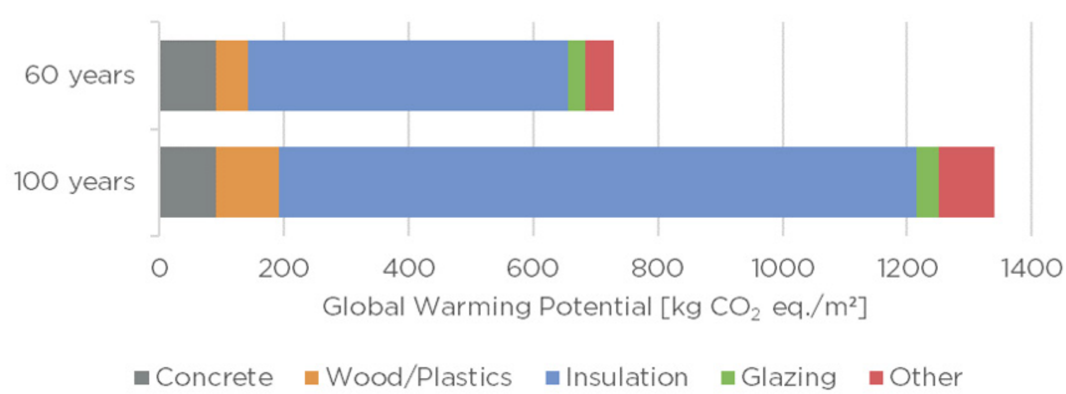


Figure 15: Variation of GWP by material for UBCO Skeena Tally assessment for 60-year and 100-year reference study periods

5.3 Benefits and challenges of project data sources

As noted in Section 2, the raw data required to generate a Building BoM can be drawn from a range of project sources. These include primary, project-specific, product-specific and secondary data sources. Throughout the Pilot, in order to develop and test our methodology, we focused on project-specific data sources, including project drawings, models and cost estimates. Generally, we used one primary data source, typically BIM models or cost estimates, and augmented those sources with information from project architectural and structural drawings when needed.

While every project will have drawings, not every project will have BIM models or cost estimates, although these are becoming increasingly common. However, as accounting for buildings' embodied carbon emissions becomes more regulated, it's important to consider the benefits and challenges of each of these data sources.

Project drawings

Project drawings are the most accurate representation of the building, especially when they correspond with an advanced design development phase, like issued-for-tender (IFT) or issued-for-construction (IFC), or are as-built or record drawings. Typically, LCA practitioners use architectural and structural drawings that provide data on the material composition and dimensions of the major building assemblies and structure of the building.

Quantity takeoffs of building material information from project drawings take a significant amount of time, even when using markup and measuring software tools such as Bluebeam Revu, and is the most time-consuming way to generate the raw data to create the Building BoM. For example, in Phase I of the Pilot, we estimated that it took the research team (who are not professional quantity surveyors) 288 hours to perform quantity take-offs from IFC drawings, compared to 44 hours to do the same from a BIM model and 27 hours from a cost estimate. This activity also requires knowledge and experience of building design, details and construction techniques, as well as the ability to read and understand the notations and drawing themselves. The practitioner's interpretation of the drawings will also depend on their familiarity with the building itself, and their assumptions and decisions will influence both the Building BoM and the results of the LCA.

BIM models

BIM models provide a 3D representation of the building elements, including their dimensions, as well as embedded information on products and materials. Extraction of information for LCA raw data is done through software tools and plugins, which take significantly less time than quantity takeoffs from project drawings. However, a fair amount of work still needs to be done by the practitioner to check that the information is accurate and translate the takeoff schedules from the BIM software into an organized BoM. There can also be errors in the material quantities exported from the software, which are not always easy to identify, in which case manual verification would be required. For example, the takeoff schedules from the TRIUMF IAMI BIM models seemed to contain tallied quantities within the lines, which were not always easy to identify and exclude as to not double count materials. It is not clear if this issue arose because of the formatting in which they were shared with the research team or because of how the model was set up from the source. Similar to the project drawings, the practitioner's ability to interpret the data quality will depend on their familiarity with the project, will include assumptions and educated guesses, and will influence both the Building BoM and the results of the LCA.

Similar to the project drawings, the accuracy of the information contained in the model varies depending on the model's level of development (LOD). For projects that only use BIM models for visualization purposes, the LOD might not correspond with the design development phase the project is in since some project teams do not keep the model up to date in parallel to the project drawings. For projects that use the BIM model to generate design development, construction, or shop drawings, the model's LOD should correspond to the appropriate design phase. However, if the design team is using multiple BIM models, such as separate architectural and structural models, certain building elements and components may be included in both models and the different BIM models may have different levels of development. This was the case with the TRIUMF IAMI architectural and structural BIM models. For example, stairs were modelled differently in the two models — it is unclear which of the two models was accurate and had the most up-to-date information, especially since stairs could potentially be modelled as under the scope of either party (architects or structural engineers). These discrepancies cause confusion, especially for the research team who had limited familiarity with the project. In the end, practitioners will need to ensure that building assemblies are not double-counted and reconcile the differences.

BIM models with a low LOD might exclude assemblies or components that are within the scope of the LCA, which would then require the practitioner to use other data sources (ideally project drawings) to fill in the gaps of the model. For example, the UBCO Skeena architectural BIM model had an appropriate level of development and generally aligned with the object of assessment, but reinforcing steel was not modelled, as is common with architectural BIM models and we didn't have access to the structural BIM model (if any). In this case, we estimated the amount of reinforcing steel based on the amount of concrete and the dimensions of the main structural concrete elements in the foundation and ground floor. This could have also been done by quantifying the rebar from the structural project drawings. However, if these other data sources and the BIM model do not align or are from different project phases, it can be confusing to coordinate information or fill in gaps across both data sources.

BIM Models with a high LOD can have the opposite issue. While they contain sufficient information, because of the high level of detail and amount of information they contain, they can be quite complicated to navigate and extracting data on discrete elements can be challenging. For example, the high level of development in the TRIUMF IAMI architectural and structural BIM models made them difficult to work with. The material grouping was complex and they contained additional elements, such as furniture, lighting and landscaping elements that had to be hidden or removed and likely contributed to the time it took the software to process material takeoff schedules. The practitioner's level of expertise with the BIM model and data extraction software, and familiarity with the building will also factor into the ease of this process and the accuracy of the organized raw data.

Specifying a BIM model's LOD is not always common practice among building designers and it is not always clear what phase of design development it corresponds to, so sometimes the LOD needs to be interpreted by the practitioner, which can lead to unknown omissions in the object of assessment. Additionally, the quality of the BIM model is also an important factor. If the model is well developed under a set of modelling best practices, the data extraction will be easier and requires fewer assumptions and interpretations than if the component parameters are not well specified or the assemblies are not well organized. Just because a BIM model of a building exists, it does not mean that it will be accurate and match with the required object of assessment for the LCA.

Cost estimates

Cost estimates provide a breakdown of Cost estimates provide a breakdown of project costs, usually by detailing estimates of assemblies and materials quantities within the building (as well as associated labour). The cost estimator, typically a quantity surveyor or construction manager, has already extracted material information from project drawings or models in order to conduct the cost estimate, reducing the time and effort required by the LCA practitioner. In the cost estimate report, the information is already organized into one of the common building classification systems, which can make the creation of the BoM an easier process.

Depending on the point in time in the project when they are conducted, cost estimates will include data with different levels of detail. Similar to project drawings, cost estimates from late stages of design development will provide the most accurate data for the actual building, in comparison to one made at conceptual design or early design development which will contain less detail and more assumptions. Therefore, the class of a cost estimate and stage of development when it was conducted is important to know, as it will impact its usability as a raw data source for the LCA.

Cost estimates are not necessarily done for all building projects, and not all cost estimate reports will include material quantity. Additionally, cost estimates are not often created with the application of LCA in mind and may not include useful information for developing the Building BoM for LCA purposes. Cost estimates might also exclude assemblies or components within the scope of the LCA, which would then require the use of other data sources (ideally project drawings) to fill in the gaps of the model. Some materials units of measure or organization might also need to be modified for LCA purposes. For example, in the Carrington View cost estimates, the footings were only quantified by number of footings and their location (32 interior pad footings, 1 elevator footing, etc.), but the dimensions or amount of concrete and reinforcing steel wasn't specified. To determine these quantities, the research team had to recur to other data sources (project drawings) to determine the dimensions for every footing and be able to calculate the material amounts in the proper units of measure for LCA purposes.

All of these data sources can be used to create the raw data needed to generate a Building BoM and then a Modified BoM for an LCA. However, in all cases, the LCA practitioner will still need to do the work to compile data that is accurate and useful for the LCA. The practitioner's decisions and assumptions, along with the accuracy and level of development of the data source, will influence the LCA results.

5.4 Evolution of the BoM throughout the WBLCA process

Through the Pilot, we have developed a 4-step process for generating a BoM and conducting a building LCA, illustrated in Figure 16. Once the raw data is extracted from the project data sources, it needs to be converted into the Building BoM, an accurate and organized list of materials and quantities in the actual building. Next, this information needs to be mapped to the selected LCA tool database, which creates a Modified BoM that can be input into the tool. The LCA tool also applies its own internal factors to this list and generates an Output BoM along with the LCA results.

The data changes with each step as the BoM evolves throughout the LCA process. As an example of the changes that occur in the process, Figure 17 illustrates the variations to the building data for a specific assembly throughout the LCA data preparation process. This table details the components within the roof assembly for the UBCO Skeena building. This project is pursuing Passive House certification and the roof, along with the rest of the envelope, is designed to provide a high degree of insulation and airtightness. The materials in the roof assembly include gypsum board, wood joists, plywood, vapour barrier, rigid insulation, batt insulation, protection board, EPDM membrane.

The last column in Figure 17 highlights some of the most significant changes to the materials and assumptions made throughout the LCA preparation process.

In generating the Building BoM, the practitioner must often consult multiple project data sources to extract or verify additional information about assembly geometry and material type. Further calculations are required to convert raw data into the final quantity with commonly used units, following the selected building classification system. The Building BoM is the most accurate reflection of the actual building.

To create the Modified BoM the practitioner must map the information in the Building BoM to the selected LCA tool. This may involve additional research into the specific materials types (from project documents or industry sources) to find the best match in the tool's database. The practitioners must also make assumptions in order to specify, generalize, substitute or exclude materials based on the options in the database. These assumptions must be documented as they impact the relevancy of the LCA results, since the Modified BoM is the information input into the LCA tool.

To create the Output BoM, the LCA tool adds additional information to the Modified BoM, such as waste factors or replacement rates based on the reference study period or additional materials such as connections

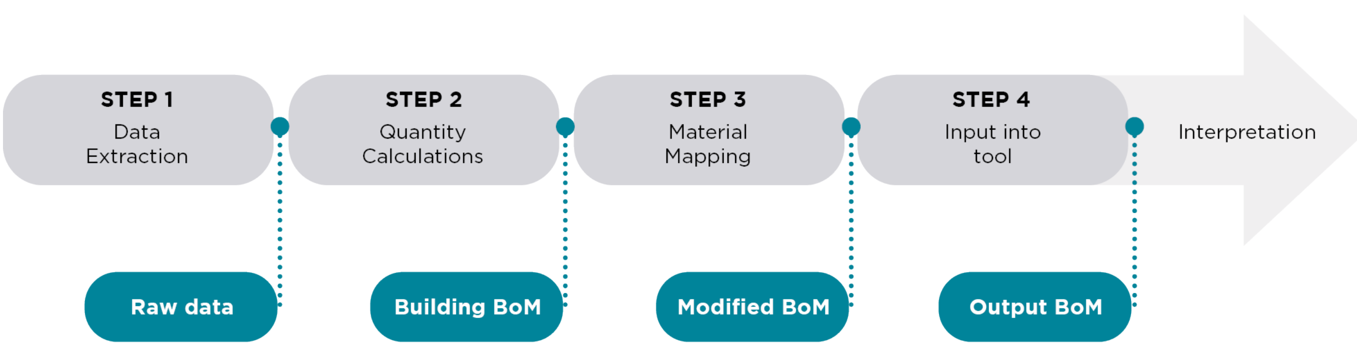


Figure 16: Overview of BoM generation process

Material	Building BoM	Modified BoM	Output BoM	Most Significant Changes
Gypsum Board	Verification of material thickness from project data source	Material specification	Waste factor added	Material specification/ mapping (not much assumption, just mapping given material to closest available option in tool's materials database)
Engineered Wood Joists	Research into joist composition Further calculations breaking up joist into constituent materials	Joist broken up into two materials (web and flange) that are input separately	Waste factor added for each material	Assembly broken up into constituent material parts
Plywood	Verification of material thickness from project data source	Conversion factor calculation	Waste factor added	Conversion factor calculation required (more work for the practitioner but shouldn't change the accuracy of material quantity total)
Vapour Barrier	-	Assumption of material specification	Waste factor added	Assumption of material specification
Rigid Insulation	Verification of material thickness from project data source	Conversion factor calculation	Waste factor added	Conversion factor calculation required (more work for the practitioner but shouldn't change the accuracy of material quantity total)
Batt Insulation	Verification of material thickness from project data source	Assumption of material specification Conversion factor calculation	Waste factor added	Assumption of R-value
Protection Board	Inquiry into project data source to try to determine material type	Research into industry standards to determine common material type Assumption of material type based on available material database in tool	Waste factor added	Assumption of material type (based on industry research into common protection board materials)
EPDM Membrane	-	Assumption of material specification	Material replacements added to material total outputs Waste factor added	Material replacements significantly increase final quantity in Output BoM

Figure 17: Variations across different BoMs in the LCA preparation process, UBCO Skeena roof assembly

or finishes based on standard construction practices. Some tools allow the practitioner to enter this information manually, while others calculate it automatically for the materials in their databases. This is the BoM that the LCA tool uses for the assessment and is the most closely connected to the LCA results.

The following table (Figure 18) shows detailed examples of four specific materials within the roof assembly and how they change throughout the process. These materials were assessed using Athena IE4B. The examples were selected to illustrate the degree of change and amount of data processing: low degree of changes, medium degree of changes and high degree of changes.

Low degree of change – Gypsum Wall Board

These materials with a low degree of change, like gypsum board, as well as plywood and rigid insulation, are generally specified quite clearly in the Revit BIM model, and no or minimal research and/or additional calculations were needed. Sheet materials needed thickness specifications and equivalent area calculations for input into Athena IE4B, but this was relatively straightforward. Material types and names in the actual Building BoM matched Athena IE4B's database closely.

Medium degree of change – EPDM Membrane

Additional research was required for the EPDM membrane, as well as the batt insulation and vapour barrier, as the Revit model and supplementary project drawings did not provide information on the material characteristics. For example, assumptions had to be made about the specifics of the EPDM membrane, such as colour and thickness. An additional complication included inconsistent reference to the EPDM membrane across multiple project data sources (while the model uses EPDM, the drawings refer to it as SBS roof membrane). The EPDM membrane's final quantity from the Output BoM is also significantly higher than the quantity input from the Modified BoM; this change occurs due to the inclusion of several rounds of EPDM membrane replacement, which is calculated by the tool based on the material's lifespan (internally specified by the Athena IE4B) and the building's reference study period (input by the practitioner).

High degree of change – Protection Board, Engineered Wood Joists

These two materials required the most work, research, and assumptions to prepare reasonable quantities for input into the tool. Because the type of protection board was not specified in the project data source, additional research and significant assumptions had to be made by the practitioner. Engineered wood joists are not an option in the Athena IE4B, so the best approximation was to break the joists into their constituent parts based on industry research and use additional calculations to separate the joists into the plywood web and small dimensional lumber flanges.

Generally, the ease of data processing and scale of assumptions required to prepare a material quantity for input into a tool relies on a wide variety of factors, the most significant of which is the alignment between the project data source and the LCA tool's materials database. If the project data source is unclearly or inconsistently organized, has unspecific material naming conventions, or makes it difficult to break down assemblies into its constituent materials, more processing is required by the practitioner. Likewise, the material options provided in the tool's materials database impact the amount of specification, generalization, or material mapping assumptions needed; the material mapping step typically involves research into various materials named in the project data source. Throughout our research, we've generally observed that the more processing required to manipulate the raw data, the more assumptions are required of the practitioner, and therefore the more potential for inaccuracies or misinterpretations that will ultimately affect the results.

Data Type	Material Name	Quantity	Units	Description
Gypsum Wall Board – Low degree of change				
Raw Data	Finishes - Interior - Gypsum Wall Board	2,156.70 34.23	m^2 m^3	Data exported from Revit Material Takeoff Schedule and organized in Excel sheets following the UNIFORMAT II classification system (B3010 Roof Coverings - some interpretation required to determine best categorization)
Building BoM	Gypsum Wall Board (Interior, finish) (15.9 mm)	2,156.70	m^2	Gypsum wallboard thickness was noted from Revit's roof assembly and verified through dividing the total volume by area
Modified BoM	5/8″ Regular Gypsum Board	2,156.70	m^2	Material mapping and specification - 15.9 mm is selected as 5/8″ thickness offered in Athena, and the regular type is selected (due to interior ceiling application)
Output BoM	5/8″ Regular Gypsum Board	2,372.37	m^2	Athena adds a construction waste factor (10% for this material) to the bill of materials output
EPDM Membrane – Medium degree of change				
Raw Data	Roofing - EPDM Membrane	1,079.15	m^2	Data exported from Revit Material Takeoff Schedule and organized in Excel sheets following the UNIFORMAT II classification system (B3010 Roof Coverings)
Building BoM	EPDM Membrane (Roofing)	1,079.15	m^2	-
Modified BoM	EPDM Membrane (black, 60 mil)	1,079.15	m^2	Revit specifies EPDM roofing, but roof assembly in drawings specifies SBS roofing. Assumption of black EPDM membrane as this is a common type
Output BoM	EPDM Membrane (black, 60 mil)	7,266.25	m^2	Athena's built-in material replacement cycles increase the final quantity (this material is replaced several times throughout the building's life). Athena also adds a construction waste factor (1% for this material)
Protection Board – High degree of change				
Raw Data	Roofing - Protection Board	1,079.15	m^2	Data exported from Revit Material Takeoff Schedule and organized in Excel sheets following the UNIFORMAT II classification system (B3010 Roof Coverings)
Building BoM	Protection Board (Roofing)	1,079.15	m^2	Research into Revit model, project drawings, and industry standards to try and determine material type
Modified BoM	Polyiso Foam Board (unfaced)	1,079.15	m^2	Assumption of polyiso as roofing coverboard/protection board (there are a variety of materials used as protection boards). Assumption of 25 mm thickness for this material
Output BoM	Polyiso Foam Board (unfaced)	1,133.10	m^2	Athena adds a Construction Waste Factor (5% for this material) to the bill of materials output
Engineered Wood Joists - High degree of change				
Raw Data	Structure - Wood Joist/Rafter - Batt Insulation	1,078.35 260.21	m^2 m^3	Data exported from Revit Material Takeoff Schedule and organized in Excel sheets following the UNIFORMAT II classification system (B1020 Roof Construction)
Building BoM	Wood Joist/Rafter (241 mm) - Web (1/2" plywood) Wood Joist/Rafter (241 mm) - Flange (2x4 lumber)	643.98 18.08	m^2 m^3	Measured average width of floor and assumed a standard spacing to calculate number of joists, used number of joists x thickness x length, and assumed flange as 2x4 sizing. Split Revit assembly into two different materials for the web and flange
Modified BoM	Softwood Plywood Small Dimensional Softwood Lumber, kiln-dried	908.73 18.08	m^2 (9mm) m^3	For Athena, plywood is only offered in 9 mm thicknesses, so a conversion factor was calculated and applied to the material's area (m^2) to represent an equivalent volume (Athena Conversion Factor: 1.4111)
Output BoM	Softwood Plywood Small Dimensional Softwood Lumber, kiln-dried	954.16 19.53	m^2 (9mm) m^3	Athena adds construction waste factors (5% for plywood and 8%for softwood lumber) to the bill of materials output as part of the LCA results files

Figure 18: Examples of material variations across different BoMs, UBCO Skeena roof assembly

5.5 Impact of high-performance envelopes on embodied carbon emissions

One of the frequent questions for embodied carbon assessments is the balance between the embodied carbon emissions of buildings with their operational emissions. As energy efficiency strategies reduce the operational energy of buildings and their associated GHG emissions, the embodied emissions become an increasing proportion of a building's carbon footprint. This balance is especially important to understand in the context of high-performance buildings, designed to Passive House or high BC Energy Step Code standards. High-performance building design seeks to reduce operational emissions as much as possible, through a combination of low-carbon fuel choices, energy-efficient equipment, and high-performance envelopes with greater airtightness and insulation. By improving the performance of the building envelope, designers can reduce the space heating and cooling loads. However, this requires more material, particularly insulation, in the building envelope. The greater material quantities may increase the embodied carbon emissions of the building, offsetting the benefits gain by reducing the operational emissions.

This Pilot was not designed specifically to assess the tradeoff between embodied and operational carbon emissions in high-performance buildings. However, we conducted a preliminary analysis to begin to understand the contribution of building envelopes to the overall embodied carbon emissions, and how different envelope designs could influence the embodied emissions of a single building.

This preliminary analysis is only for discussion purposes. Additional research is needed across multiple projects to more thoroughly understand the types of impacts high-performance envelopes and their specific material compositions can have on a building carbon footprint and potential tradeoffs between operational and embodied carbon emissions.

5.5.1 Envelope comparison – all buildings

As a first step, we isolated the envelope for all the buildings and analyzed the GWP results for the envelope compared to the overall GWP impacts (Figure 19). In this case, the building envelope includes all assemblies that separate the interior conditioned environment of the building from the exterior unconditioned environment. Generally, this includes foundation, exterior walls, exterior doors, exterior windows, and roofs. We used a system boundary that included production, construction, use and end of life (modules A to C, excluding B6 operational energy use and B7 operational water use) and an assessment period of 60 years for all the buildings. The LCAs did use different tools, indicated as (T) Tally, (A) Athena IE4B, or (1C) One-Click LCA.

Overall, the range of GWP impacts of the building envelope varied significantly across the projects, between 22-81% of the overall impacts. 2150 Keith Drive has the lowest impact envelope, even though it is designed to achieve the highest levels in the BC Energy Step Code. SFU Parcel 21 has the highest impact envelope of the buildings assessed by Athena IE4B and UBCO Skeena has the highest from the buildings assessed with Tally. The average across all the assessments is around 50%.

SFU Parcel 21 and UBCO Skeena are both high-performance buildings, pursuing Passive House certification. Their designs therefore include robust envelopes with greater volumes of materials, so it makes sense that their envelopes would be a high proportion of their overall GWP impacts. One of the primary envelope materials for 2150 Keith Drive is CLT, which may have contributed to its lower proportional contribution to the building's GWP impact. However, the 2150 Keith Drive BIM model was also challenging to use for the assessment due to how the assemblies were modelled and labelled, which could have resulted in an oversimplification of the envelope assemblies.

The different results from the two assessments on UBCO Skeena and TRIUMF IAMI illustrate the variation between tools and their databases. Although both are based on the same data sources and Building BoM, there are differences between the percentage of envelope impacts as assessed by Athena IE4B and Tally. For TRIUMF IAMI, this difference is minor, only 1%. For UBCO Skeena, however, Athena IE4B estimated the building envelope to contribute 53% percent of the total GWP impacts, while Tally estimated the building envelope to contribute 81%. This significant variation could be due to different sources of material data in their databases and different scenarios for certain materials, or to different categorization of envelope assemblies in each tool's internal classification system. It's possible that one tool under or overestimates the impacts of certain materials.

This assessment illustrates the significant contribution that building envelopes can make to the overall embodied carbon emissions of a building, as well as the inherent variations and uncertainties when conducting LCAs.

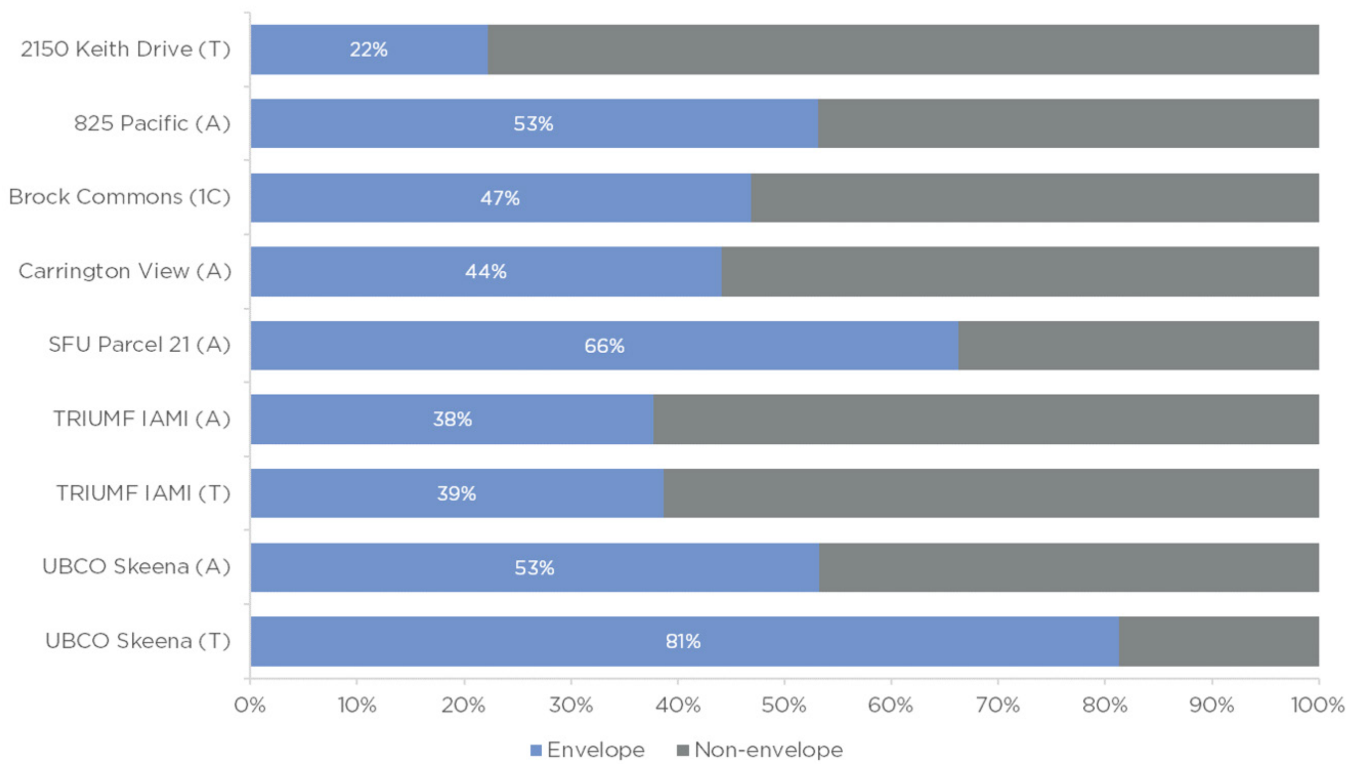


Figure 19: Proportion of GWP from building envelopes (module A-C) for all assessments

5.5.2 Carrington View – base vs. proposed building

To further explore the potential impacts of building envelopes, we compared two design options for the Carrington View project. The project team created two detailed cost estimates for a conventional code-compliant version and for a high-performance version of the building designed to achieve Step 4 of the BC Energy Step Code. The most significant differences between these options were in the exterior wall construction, specifically the window glazing, insulation, and structural material. By isolating these assemblies, we were able to analyze the GWP impact of a conventional exterior wall designed to code and a high-performance largely pre-fabricated exterior wall design.

The base wall design is composed of vinyl cladding, wood stud framing, R-22 batt insulation, vapour barrier, and gypsum board. The exterior windows are double-glazed with PVC frames. The proposed (high-performance) wall design is composed of vinyl cladding, R-40 pre-fabricated SIP panels, vapour barrier, and gypsum board. The exterior windows are triple-glazed with PVC frames.

The GWP of the envelope for the base building is 17.9 kg CO_2 eq/m^2, and for the proposed building it is 25.4 kg CO_2 eq./m^2, an increase of 35%. As observed in Figure 20, the envelope accounts for 17% of the total building impacts in the base building, and for 44% of the total building impacts in the proposed high-performance building.

When zeroing in on the envelope broken down by element (Figure 21), we can observe that in the base design, the windows (glazing and frames) were the largest GWP contributor by a significant margin: 52% of the total envelope impact. In the proposed design, however, the insulation is the largest GWP contributor (45% of the total envelope impact), with the windows (glazing and frames) a close second (35%). The largest difference is the insulation, the GWP contribution from the 8.25’’ thickness of EPS insulation in the proposed design is significantly greater (45%) than the contribution from the 5.5’’ minimum thickness of batt insulation in the base design (19%).

It should be noted that the double-glazed PVC windows have a slightly greater impact than the triple-glazed PVC windows. The research team input the material quantities for the windows by size and then selected double or triple-glazed in the LCA tool. The difference could be due to variations in the proportion of window frame to glazing or due to variations in GWP impacts between the two types of products in the LCA tool database.

This preliminary analysis shows that there are potentially significant GWP impacts from insulation in high-performance building envelopes. Although outside the scope of this Pilot, a more detailed analysis of the GWP impacts of different types of insulation and different thicknesses could help inform design guidelines for these assemblies.

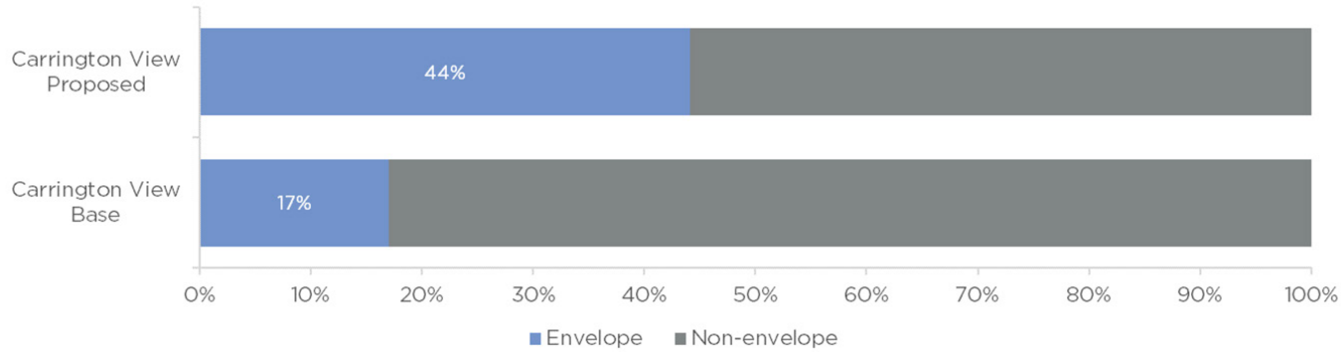


Figure 20: Proportion of GWP from building envelopes, Carrington View base and proposed buildings

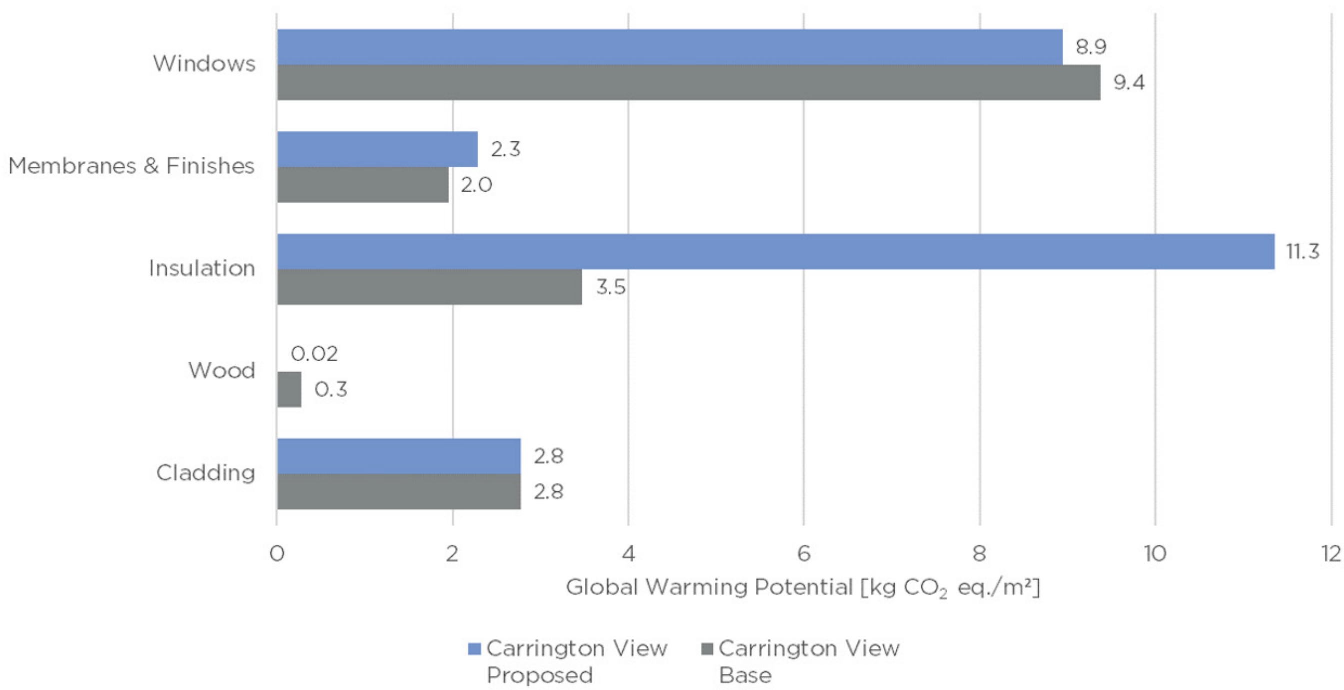


Figure 21: GWP of envelope materials, Carrington View base and proposed buildings

5.6 Impact of materials on embodied carbon emissions

Generally, two of the most common ways for LCA results to be displayed are by life cycle stage and building element category, but results can often be broken down by material as well. The material breakdowns are based on the material categories in the building classification system and include all the impacts from all materials in the building within that category, independent of the building element or life cycle stage. While certain materials, like concrete, are primarily structural materials, others, like metals, are used throughout the building in structural, interior partitions and envelopes. This is one of the challenges with material breakdowns in WBLCA: unless the object of assessment is limited to one building system it can be difficult to isolate individual materials in that system. This is partially why a practitioner would limit the scope of a design-decision LCA to a specific building element to better compare multiple options.

In order to understand the impacts that the material breakdowns have on the embodied carbon emissions of the buildings, we broke down the total building GWP impacts by material category. These are shown in Figure 22, with the materials as percentages of the total building GWP impacts. We used a reference study period of 60 years for all buildings, and the life cycle stages include product, construction, use and end of life (modules A-C).

There is a wide range of variations in the material breakdowns of GWP across the different building projects, which reflects the variations in purpose and design. However, variations may also be due to the different sources of underlying material data and scenarios in the tools. There is a considerable level of uncertainty associated with the quality and consistency of underlying material data in WBLCA tools, including issues such as data vintage, regional applicability, LCI background data and LCIA method. Issues with the underlying data in the tools affect the utility, reliability and comparability of LCA results.

In terms of similarities within the material breakdown for the different buildings, materials associated with structure and foundation, such as concrete, contribute to around half or more of the GWP impacts in most of the buildings. Wood and insulation are other significant contributors to some projects as well.

TRIUMF IAMI has by far the largest amount of concrete, rebar and other metals. This is due to the highly specific function of this building, including specialized labs and a cyclotron, which require thick concrete walls. The specialized nature of this building was an inhibiting factor in the project team conducting an LCA for the purposes of LEED since the functional requirements of the building are more critical than the environmental impacts.

UBCO Skeena Residence is an outlier in this assessment, as the impacts from concrete and metal are low and insulation is the major contributor to the GWP impacts. This project is pursuing Passive House certification which requires better insulated envelopes to stabilized internal heat gains and losses and reduce operational energy demands, and the insulation in the envelopes is significantly thicker than a conventional building. UBCO Skeena also has a primarily wood-frame structure, which is why wood is also a notable contributor to GWP impacts.

In the two buildings with multiple assessments using different tools, Figure 22 illustrates more of the variations between the tools and databases. For TRIUMF IAMI, the Tally and Athena IE4B assessments have similar profiles, although the specific percentages are different. The proportion of rebar to other metals is opposite, with Tally assigning more impact to rebar than other metals, while Athena IE4B assigns more impacts to metals than to rebar. In UBCO Skeena, the Tally assessment shows a heavy weighting towards the impacts from insulation, while the Athena IE4B assessment has a more even breakdown of impacts across different material categories. This difference could be from how each tool categorizes certain materials, as well as the variations of different sources for the underlying material data and different scenarios employed by the tools.

Variations in materials highlight the different types of opportunities for project teams to reduce embodied carbon emissions in their buildings. In TRIUMF IAMI, for example, the large volume of concrete creates an opportunity to look for reducing cement content through additives, provided the functional needs of the facility can be maintained. In UBCO Skeena, the large impact from insulation creates an opportunity to investigate low-carbon products that still meet the performance criteria for Passive House certification.

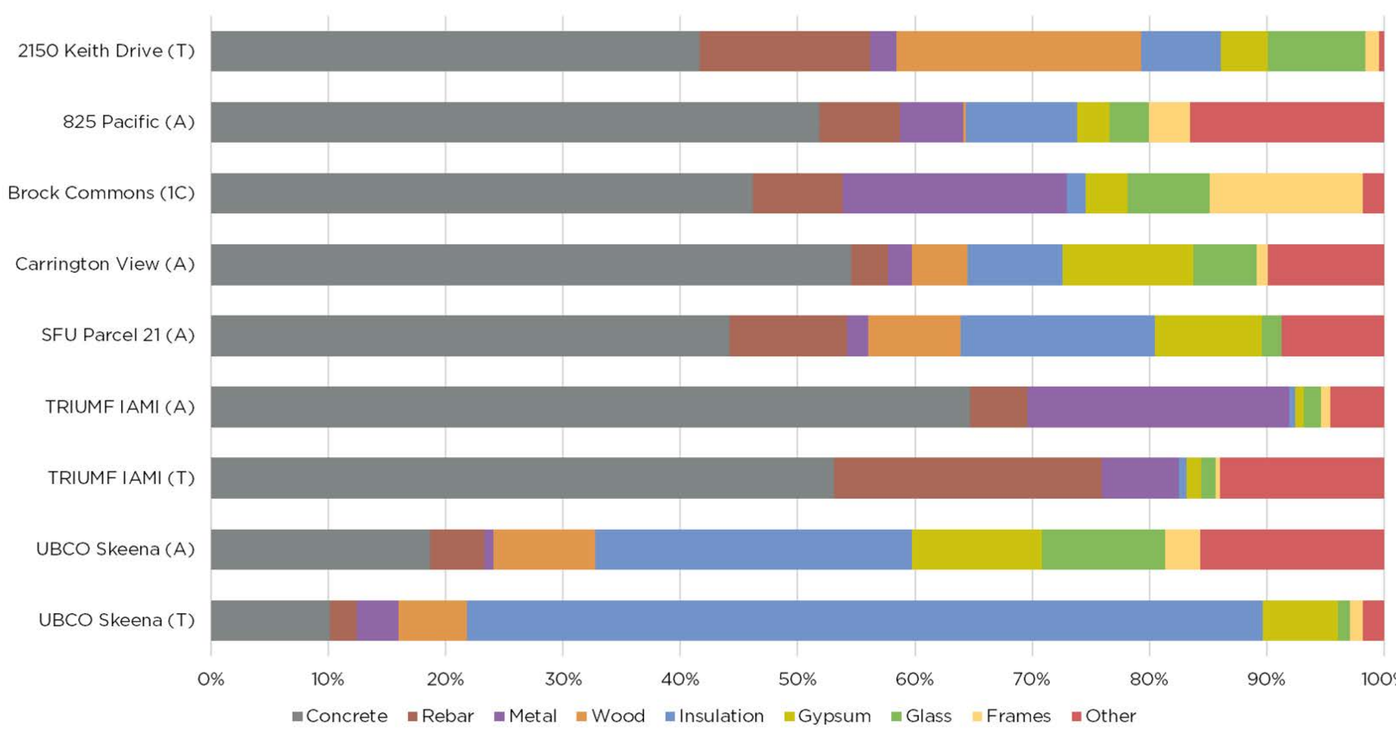


Figure 22: Proportion of GWP by material (modules A-C) for all assessments

6

PILOT NEXT STEPS

The Embodied Carbon Pilot is a multi-year research project to better understand the practice of conducting LCA to measure a building's embodied carbon emissions (or GWP), and how they can be used effectively to inform policy benchmarking and performance targets. The objective of Phase 1 was to explore the process of conducting embodied carbon assessments and to analyze the factors that may affect the consistency, reliability and variability of the results. Through this work, we identified a set of parameters and procedures that together create a framework for conducting building LCA to calculate embodied carbon.

During Phase 2, we built on this work to develop a methodology that interprets the LCA process outlined in the ISO 14040 standard (Environmental Management – Life Cycle Assessment Principles and Framework) into a set of decisions and steps to scope an LCA, create a quantified list of building materials, choose a WBLCA tool and conduct the assessment. The methodology identifies a number of factors that need to be determined by the practitioner before conducting an LCA, including the goal, scope, available data sources and appropriate WBLCA tool, and then outlines a four-step process to prepare the project material information for input into the tool for assessment. The primary focus on Phase 2 was to develop and then test this methodology, by applying it to conduct LCAs on seven different B.C. building projects. The methodology proved to be a useful and effective approach to creating a BoM and conducting LCA. It is outlined in the early sections of this report and will be published as a standalone white paper.

For Phase 3, we are continuing to build on our experience and learning from Phase 1 and 2 with a more explicit focus on the requirements and protocols for embodied carbon benchmarking. We will use the methodology developed in Phase 2, as well as the project information and LCAs conducted over the previous years, to refine the process of conducting LCA to calculate embodied carbon in buildings for setting benchmarks and performance targets. The first part of Phase 3 will include a technical analysis of the parameters for developing a building BoM for LCA to inform a draft set of variables or ranges for each parameter. In parallel, we will consult with practitioners to understand the current state of practice of LCA in the building industry. The second part of Phase 3 will include the creation of a pilot BoM database, using project information from Phase 1 and 2, and testing and analyzing the impacts of different variables on the LCA parameters.

As in Phase 1 and 2, the processes of data collection, organization, LCA and analysis will be documented and studied. In addition to setting appropriate benchmarks and targets, the reporting and compliance requirements to meet new policies or regulations must not create an unreasonable burden for project teams. By studying the processes themselves, we are able to identify challenges and information gaps, as well as possible synergies and alignment with existing development activities and project documentation. This information, along with the learnings from the pilot BoM database and parameter variables, can all help inform the creation of new guidelines and policies that can help reduce the embodied carbon emission from buildings.

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