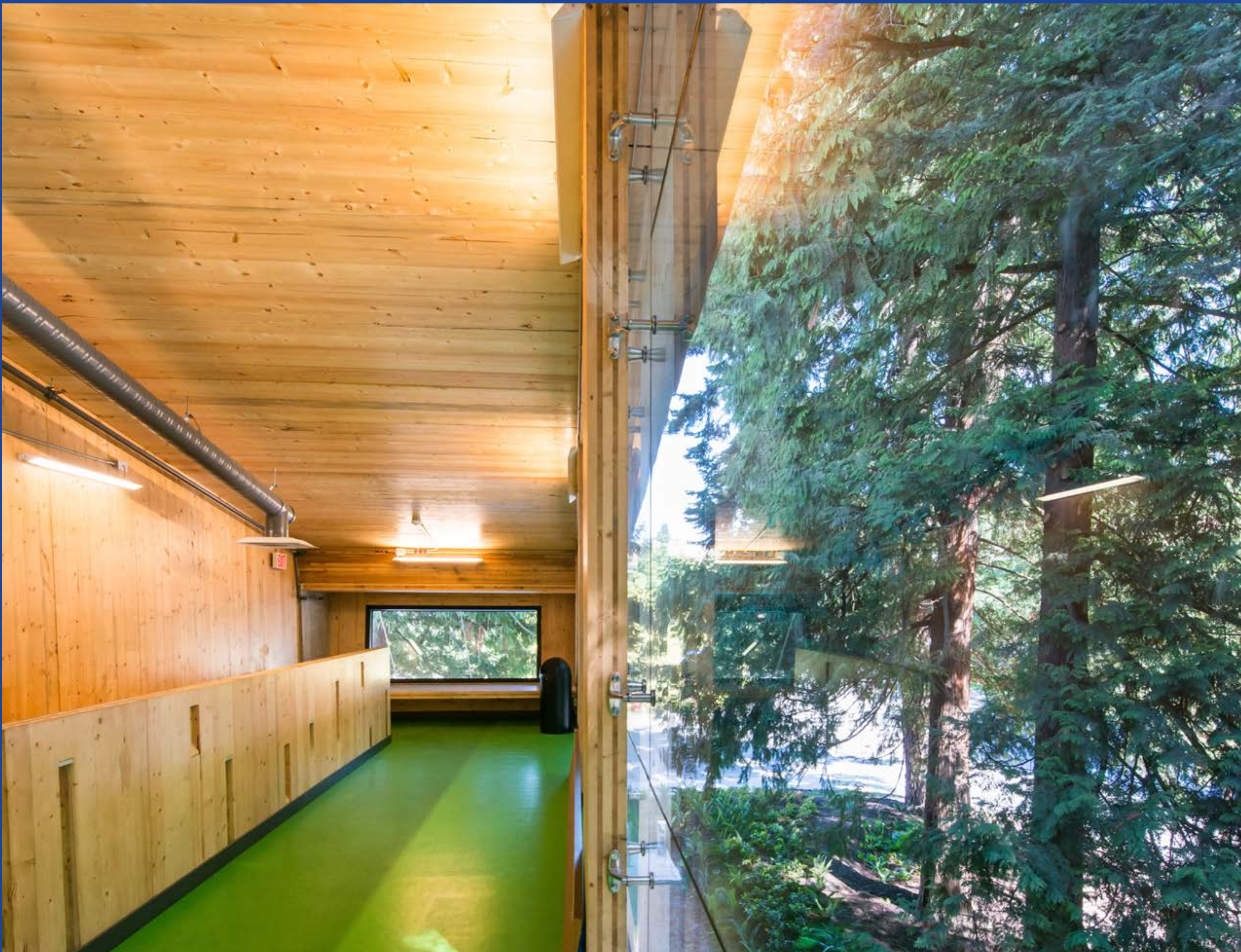
UBC EMBODIED CARBON PILOT

Bill of Materials Generation Methodology



THE UNIVERSITY OF BRITISH COLUMBIA
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The paper describes the LCA parameters and methodology developed and applied as part of Phase II of the Embodied Carbon Pilot.

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CONTENTS

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,

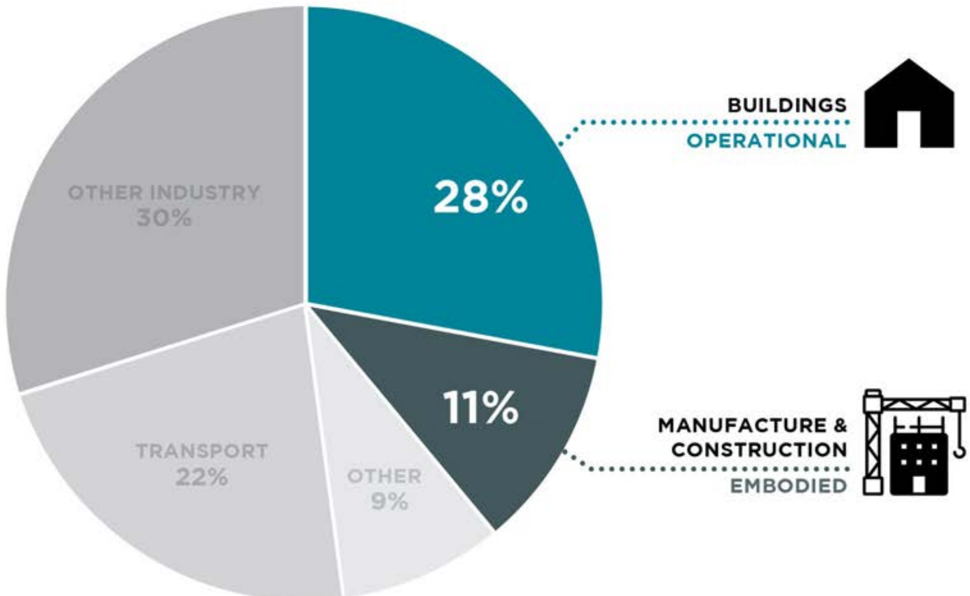

Figure 1: Share of global energy-related CO_2 emissions (adapted from Global Status Report, 2017)

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 paper 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 paper 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 paper 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 paper 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 paper 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. Section 4 discusses the limitations of this method, including future considerations for the interpretation phase.

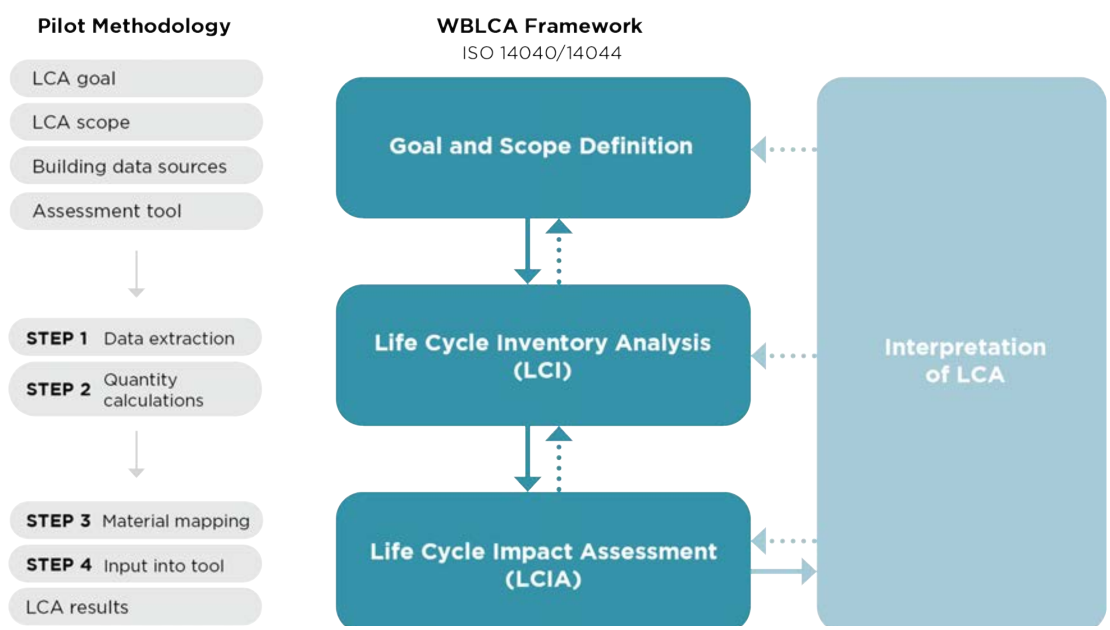

Figure 2: LCA process per ISO 14040:2006 and correlation with the Pilot methodology

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 this 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.

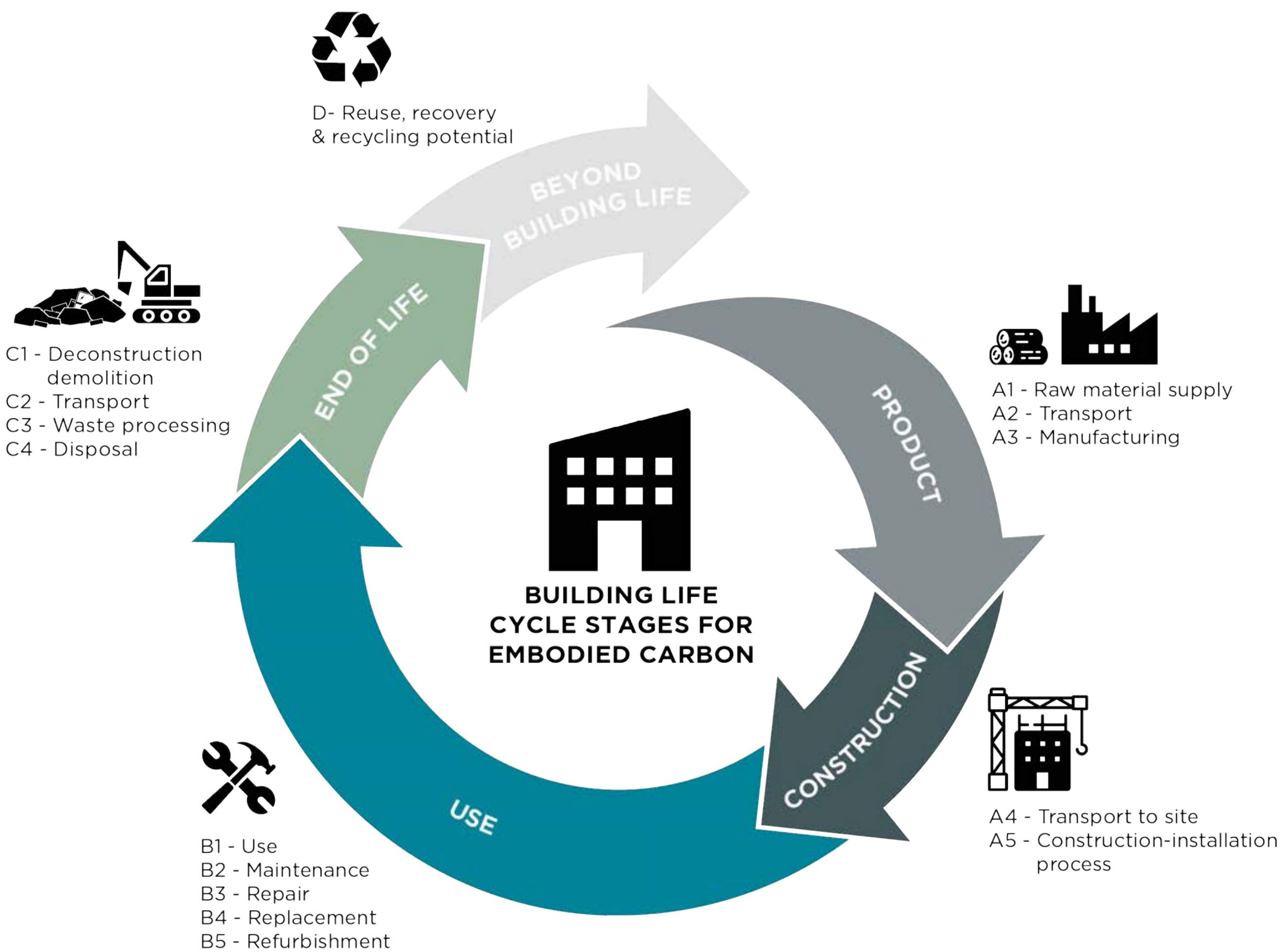

Figure 4: Embodied carbon building life cycle stages and modules per EN 15978:2011

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 paper. These steps are described in detail in Section 3.3.

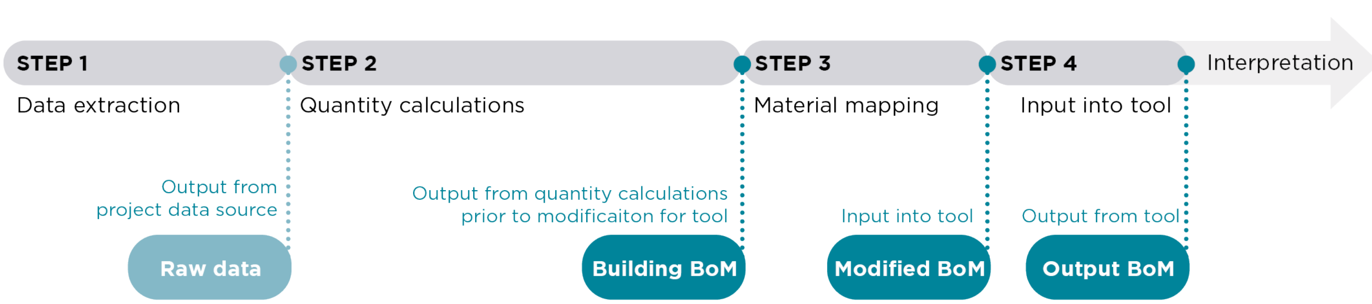

Figure 5: BoM generation process and the BoMs produced in each step

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 paper 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.

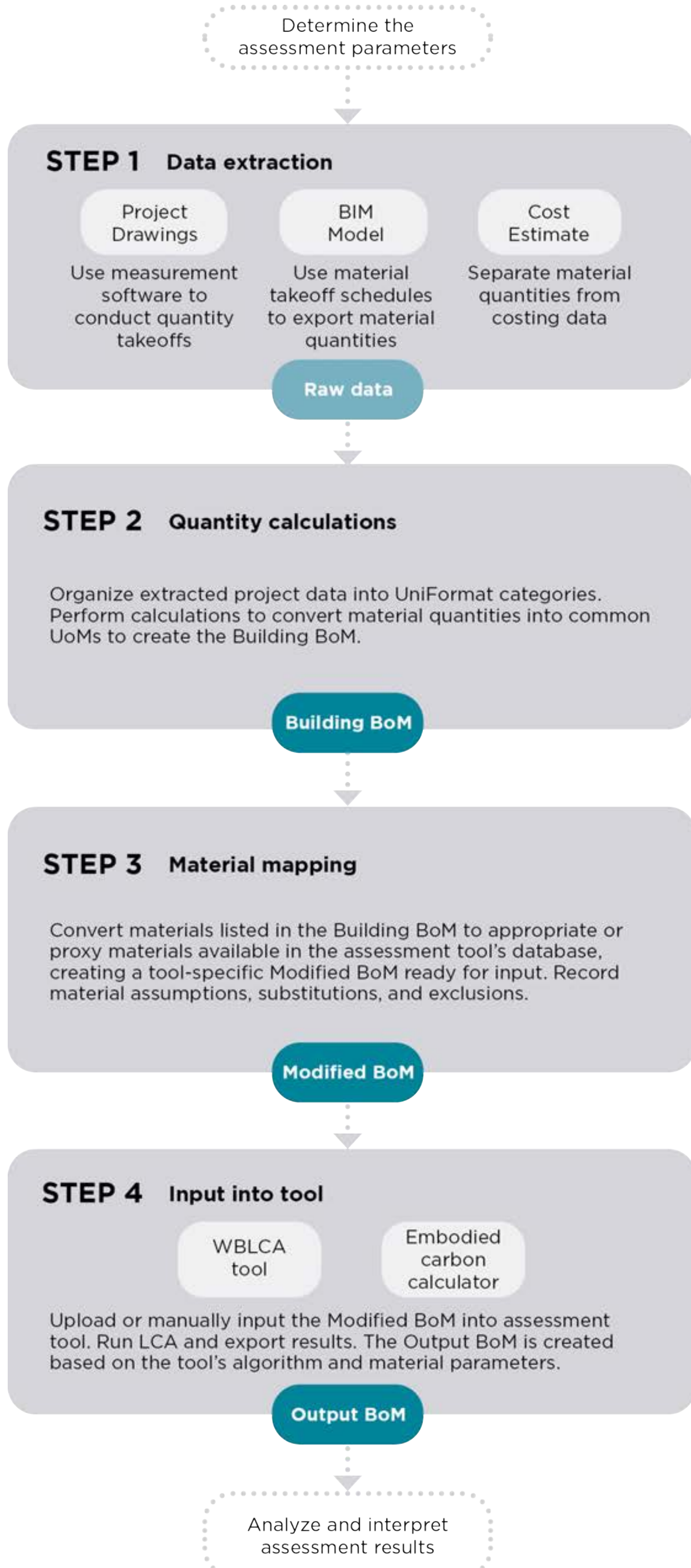

Figure 6: Overview of BoM generation methodology for building LCA

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.

4 METHODOLOGY LIMITATIONS

There are other 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. 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 paper 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.

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