# Life Cycle Assessment of Buildings: *A Practice Guide*


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# Life Cycle Assessment of Buildings:
# *A Practice Guide*

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The members of the advisory committee are listed below. Their contributions were critical to the development of this document and are greatly appreciated. Individuals who went above and beyond are recognized in bold text.

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# About

This Practice Guide introduces the use of life cycle assessment (LCA) to analyze the environmental impacts of buildings. The intent of this Practice Guide is to help building professionals understand why and how to use LCA in their work.  It addresses basic questions such as:

- How do buildings impact the environment?
- What is LCA and how is it used to evaluate buildings?
- What is the process of performing an LCA of a building?

The first part of this Practice Guide is the **Introduction**, which describes how buildings affect the environment and how LCA can be used to quantify environmental impacts.  The second part of the Practice Guide is the **Implementation**, which presents the five key steps to conducting an LCA of a building.

This Practice Guide is accompanied by a supplemental web page containing **Online Resources**, which includes technical guidance documents for LCA tool developers and experts, and a growing list of building-related LCA resources, including building-specific LCA tools or software.

The navigation bar of the document, shown on the right edge of each page, reflects the general structure of this Practice Guide.

Although this Practice Guide caters to a North American audience, the principles of LCA are generally applicable to any geographic region, with differences residing in the relevant standards, rating systems, datasets, and tools.

# Abbreviations

| | |
|---|---|
| **AP** | Acidification potential |
| **$CO_2$(e)** | Carbon dioxide (equivalent) |
| **EN** | European Standard (French: “norme”, German: “Norm”) |
| **EPA** | Environmental Protection Agency (United States) |
| **EP** | Eutrophication potential |
| **EPD** | Environmental product declaration |
| **EUI** | Energy use indicator |
| **FSC** | Forest Stewardship Council |
| **GHG** | Greenhouse gas |
| **GWP** | Global warming potential |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISO** | International Standards Organization |
| **kg** | kilograms |
| **LCA** | Life cycle assessment |
| **LCI** | Life cycle inventory |
| **MEP** | Mechanical, electrical, plumbing |
| **NGO** | Non-governmental organization |
| **NIST** | National Institute of Standards and Technology |
| **ODP** | Ozone depletion potential |
| **ReqSL** | Required service life |
| **RSP** | Reference study period |
| **SFI** | Sustainable Forestry Initiative |
| **SFP** | Smog formation potential (also known as “formation of tropospheric ozone”) |
| **UK** | United Kingdom |
| **UN** | United Nations |
| **US** | United States |
| **UV** | Ultraviolet |
| **VOC** | Volatile organic compounds |

## Part A
# Introduction

## How do buildings impact the environment?

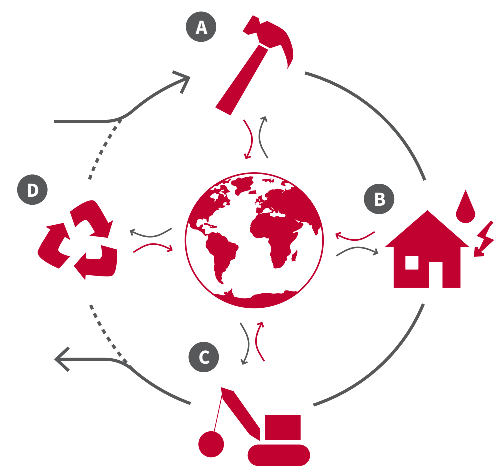
Constructing a building and using it for many years produces long-lasting impacts on human health and the environment. *Life cycle assessment (LCA)* is the rapidly evolving science of illuminating these impacts in terms of their quality, severity, and duration.

A building generates environmental impacts throughout its *life cycle*. The various stages of a typical *life cycle* as defined in LCA are:

- A: the production and construction stages,
- B: the use stage,
- C: the end-of-life stage, and
- D: externalized impacts beyond the system boundary.

The *production stage* involves the energy and resources used to extract raw materials, to transport the materials to product manufacturing facilities, and to produce the final building products. The *construction stage* involves the transportation of materials to the construction site as well as the energy used to power the construction equipment, to supply supporting construction materials, and to dispose of any waste generated during the construction process. The *use stage* involves the impacts of occupying a building over its lifetime due to lighting, heating, water use, and any materials used for maintenance, repairs, and replacement. The *end-of-life stage* involves the demolition and disposal of the building as well as waste processing (if the building is not repurposed or improved for further occupancy or use). Finally, the last stage gathers all of the miscellaneous effects of reusing, recycling, and/or recovering materials, energy, or water from the project. These effects are called *externalized impacts* because they are manifested outside of the *system boundary*, which is defined as the physical limits of the LCA study.

Throughout the life cycle stages of a building, emissions and other pollutants are produced and released into the surrounding environment. A visual depiction of where these emissions may occur during a building's life cycle is shown in **Figure 1**.




### Cradle? Gate? Grave?

The beginning of the life cycle is also referred to as the "cradle," while the exit point of the manufacturing facilities is known as the "gate," and the end of the life cycle is known as the "grave." Thus, terms such as "cradle-to-gate" and "cradle-to-grave" are used to refer to different ranges of the life cycle.

# Carbon Cycle in the Built Environment

**A** **Product Stage**
Raw Material Supply
Transport (to Manufacturing)
Manufacturing
Transport (to Site)
Construction Installation

**B** **Use Stage**

**C** **End-of-Life Stage**
Deconstruction/Demolition
Transport
Waste Processing
Disposal

**D** **Beyond System Boundary**
Reuse, Recovery, and
Recycling Potential

Extraction from Nature
Emissions to Nature

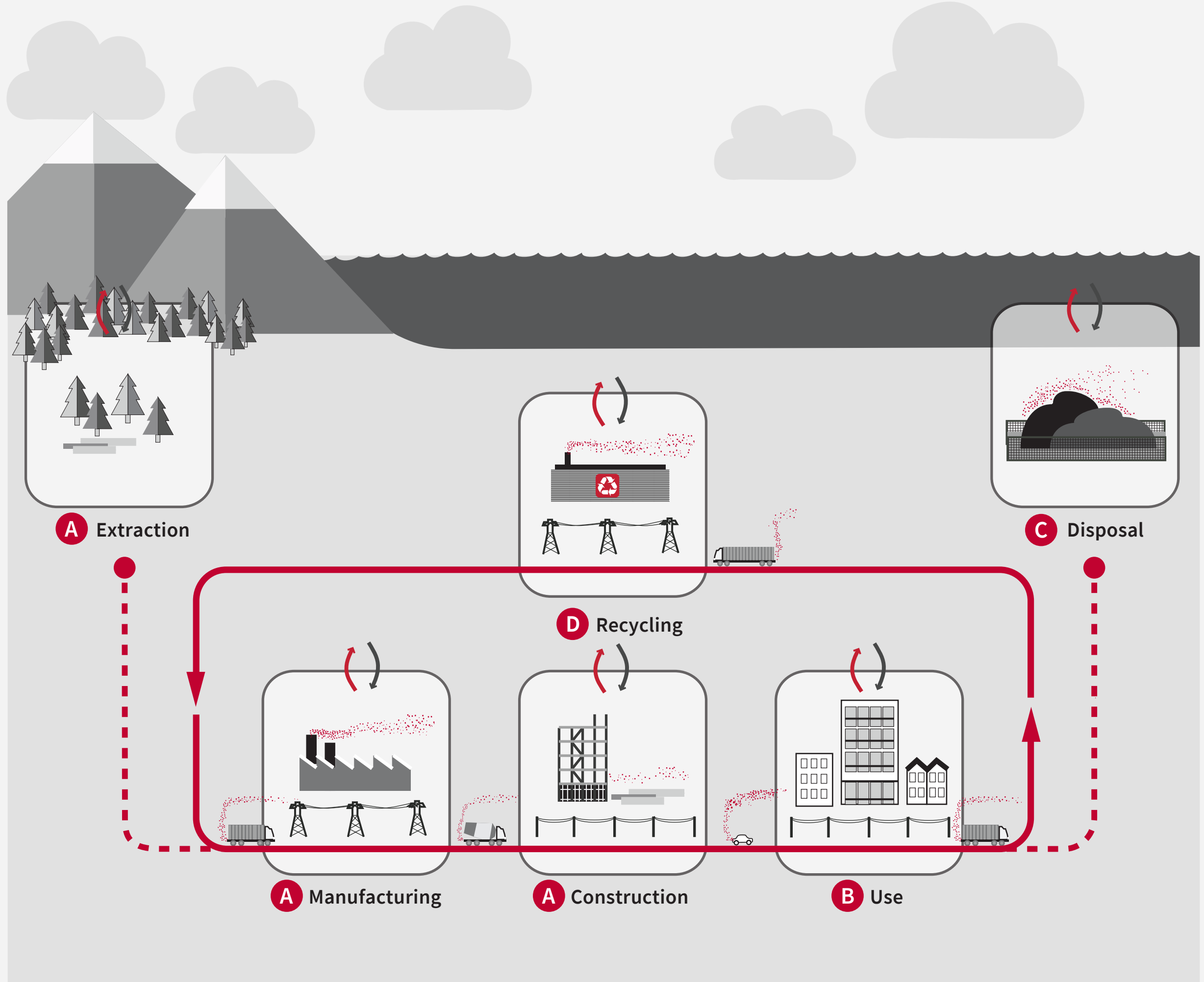



Figure 1. Sources of emissions by life cycle stage (A, B, C, D) of a building based on stage definitions from European Standard (EN) 15978 (credit: Meghan Lewis).

## What are emissions and why do they matter?

LCA tracks *emissions,* which are substances released into the air, water, or soil. Emissions and other pollutants can adversely affect the environment and human health in a variety of ways. Of key importance are *greenhouse gas (GHG) emissions*, which contribute to the disruption of the global climate. Climate change is projected to undermine food and water security [1], but ongoing effects are already devastating, especially for those who are geographically or economically vulnerable to droughts, flooding, and other natural disasters.

The continued use of fossil fuels is of particular concern in the modern age. The built environment is sustained directly and indirectly by the combustion of fossil fuels and accounts for nearly half of the energy produced in the United States through the construction, operation, and demolition of buildings [2]. Given the building industry's enormous global footprint, industry professionals stand in a critical position to cease causing – and start healing – the warming climate.

## How are emissions translated into environmental impacts?

Emissions associated with materials and products are typically estimated from computational models or are based on actual measurements [3]. Emissions are translated into environmental impacts by multiplying their masses with *characterization factors.* LCA assesses a number of *environmental impact categories,* which are broad measures of environmental change, encompassing the effects of many types of emissions. The five most prominent environmental impact categories used in US green building initiatives and LCA tools are as follows:

- **Global warming potential**: Describes potential changes in local, regional, or global surface temperatures caused by an increased concentration of GHGs in the atmosphere, which traps heat from solar radiation through the "greenhouse effect." This impact category is strongly correlated with two others – acidification and smog formation – because global warming is largely driven by the burning of fossil fuels, which also directly contributes to these two impact categories.

### The many names of "carbon"

The following is a list of terms that are often used somewhat interchangeably to refer to the emissions associated with climate change or global warming [1]:

- Carbon
- Carbon footprint
- Carbon dioxide ($CO_2$)
- Carbon dioxide equivalent ($CO_2$e or $CO_2$eq)
- Greenhouse gas (GHG) emissions
- Fossil fuel emissions
- Global warming potential (GWP)
- Climate change (CC) potential

These terms do not share the exact same meaning. Even though the term "carbon" is commonly associated with climate change, it is technically not elemental carbon that contributes to climate change, but carbon dioxide gas along with many other substances such as nitrous oxide and methane. Nevertheless, "carbon" is often used as an abbreviation to refer to global warming potential.

### Embodied and operating carbon

LCA can assess many environmental impacts, but GWP is often the focus of LCA studies. *Embodied carbon* commonly refers to the GWP attributed to materials and energy used in the construction and maintenance of buildings. *Operating carbon* refers to the GWP attributed to operation and use of the building.

- **Acidification potential**: Describes the acidifying effect of substances in water and soil. Acidification can occur when substances such as carbon dioxide dissolve in water and lower the pH levels, increasing the acidity of the water. In LCA, this terms refers to the local effects of acidification. However, on a global level, ocean acidification threatens the survival of certain species and jeopardizes marine food supplies for humans [1]. Additional potential effects of acidification include the destruction of forests and erosion of building materials [5].
- **Eutrophication potential**: Describes the effect of adding nutrients to soil or water, causing certain species to dominate an ecosystem and compromise the survival of other species. An example of this is when an overgrowth of algae depletes water oxygen levels and kills off fish. Fertilizers are a dominant of eutrophication.
- **Ozone depletion potential**: Describes the degrading effect of substances in the stratosphere on the ozone layer, weakening the ozone layer's ability to prevent excessive ultraviolet radiation from reaching Earth's surface. The Montreal Protocol has effectively mobilized global engagement to address this issue [6], [7]. Ozone impacts from building materials are rarely significant, but refrigerants used in mechanical systems are an area of concern.
- **Smog formation potential**: Describes the presence of substances such as carbon monoxide and volatile organic compounds (VOCs) in the atmosphere, forming photochemical smog. Smog is harmful to human health (e.g. causing respiratory issues) and ecosystems (e.g. causing deterioration of crops).

In the US, the EPA has published characterization factors in the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) [4]. Other characterization factors are used in other regions. Databases known as *life cycle inventories (LCIs)* report these emissions for different processes that contribute to the creation of a material or product. Different LCIs reflect differences in regional practices and manufacturing processes.

### Where do life cycle inventories come from?

Life cycle inventory (LCI) databases are created and managed by governmental, non-governmental, and private organizations. These LCI databases are used to create building industry-specific LCA data to integrate into tools, which is where most building industry professionals can access LCA data. See the **Online Resources** for more information.

In an LCA of a building, all of the material and process quantities are gathered into a body of information known as the *inventory* and multiplied with the appropriate impacts for each material or process.  The overall results are summed to obtain the overall environmental impacts of a building.  A simple example of the calculation process is shown in **Figure 2**.

## How is LCA used in the building industry?

In the building industry, LCA is commonly used to:

- Help building owners make informed choices regarding sustainability and/or resilience
- Evaluate design options by providing insight into materials choices and their environmental impacts
- Achieve green building certification (e.g. in LEED v4 or Living Building Challenge)
- Assist in assessing the environmental benefits of new products and/or policy
- State that a system or product is environmentally preferable to another (to make a *comparative assertion*)
- Compare to benchmarks to evaluate a building's performance

The results of an LCA can illuminate which parts of a building have particularly high environmental impacts.  This type of *hot-spot analysis* can help the design team achieve a more environmentally conscious design.  However, any design modification should be evaluated with another round of

| INVENTORY | | IMPACTS | | TOTAL |
|---|---|---|---|---|
| Estimate of quantities of materials and processes in building | × | Estimate of environmental impacts for each material and process | = | Estimate of total environmental impact of building |

EXAMPLE CALCULATIONS

| | | | | |
|---|---|---|---|---|
| 100 kg steel | × | 0.43 kg $CO_2$e /kg steel | = | 43 kg $CO_2$e |
| 50 kg glass | × | 1.064 kg $CO_2$e /kg glass | = | 53.2 kg $CO_2$e |

**Figure 2**. Simple example of LCA calculation process.

### What is a benchmark?

A benchmark is "a set of environmental impact results that serve as a reference point from which the relative performance of other buildings can be evaluated" [8].  Benchmarks for operational energy efficiency are measured using energy use intensity (EUI).  Efforts to develop building-level LCA benchmarks are under way in North America [8], [9], and are more advanced in Europe.

LCA. For example, changing the structural material of a building from concrete to steel would affect the insulation design due to the differing thermal properties of concrete and steel. The insulation components would then have to be redesigned before the LCA is performed again.

In design practice, LCA can be used as a comparative model aimed at making incremental improvements and evaluating design options. Simply put, LCA helps designers evaluate the environmental consequences of different designs by comparing buildings, materials, or assemblies.

This iterative process of LCA is expanded upon in the next part of the Practice Guide: **Implementation**. A preview of the steps for conducting an LCA is shown in **Figure 3**, which illustrates the iterative process of LCA. The dashed lines indicate the potential paths of iteration through the LCA process.

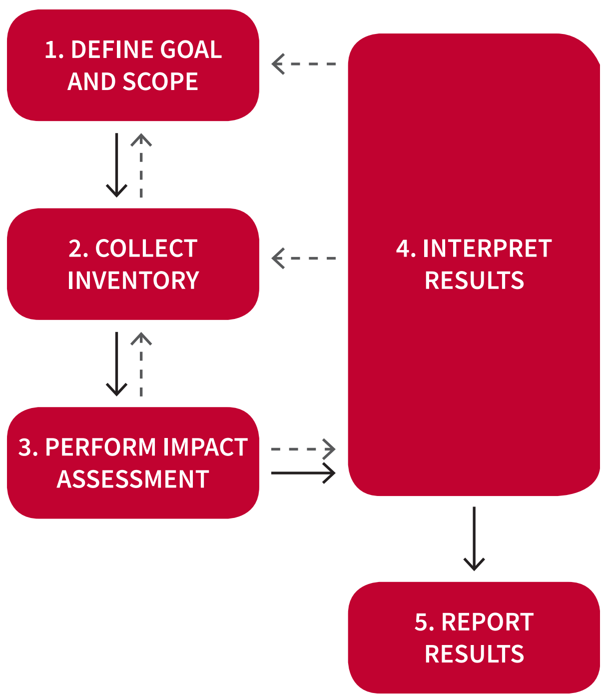



**Figure 3**. Simple diagram of LCA process.

## Part B
# Implementation

# Overview

A good LCA is meant to be methodical and transparent, much like the scientific method. There are a number of official standards [8], [9], [10], [11] that formalize the practice of LCA. These standards are generally quite flexible, which may make performing an LCA easy in some ways, but more challenging in other ways. For example, it can be difficult to make the following decisions in an assessment:

- What components of the building should you include? What constitutes a “whole building LCA”?
- Which life cycle stages should you include?
- Which data source(s) should you use?

EN 15978 [10] is a European standard that has been developed specifically for assessing the environmental performance of buildings, and it helps answer these kinds of questions. However, it was developed in a European context and is somewhat open-ended, so North American building professionals may find it challenging to implement. In the US, ASTM E2921-16a provides “minimum criteria for comparing whole building life cycle assessments for use with building codes, standards, and rating systems” [12] but it is not as comprehensive as EN 15978.

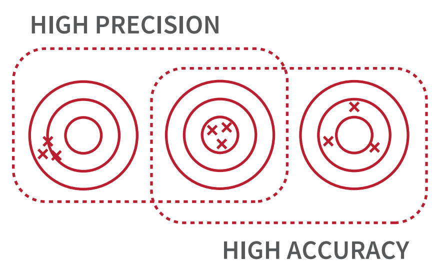
This Practice Guide, coupled with the companion *Technical Guidance* found in the **Online Resources**, aims to bridge the gap between EN 15978 and LCA practice in the North American building industry. It should be noted that the Technical Guidance, which is a separate document, is directed more towards seasoned LCA practitioners and tool developers in order to help improve the rigor and alignment of North American LCA tools and data.

Although the process of conducting an LCA is outlined as a series of steps, LCA is often an iterative exercise. As you learn more about your building and potentially reassess the goal and scope of your study, you should expect to cycle through the different steps multiple times.

You can perform an LCA at different stages of design or construction of your building. As the design becomes more developed or as construction begins, you will also be able to define the building with increasing levels of precision and accuracy.

### Accuracy vs. Precision

Accuracy refers to how close a measured value is to the standard or true value. Precision refers to how close the measured values are to each other. See graphic below.

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# Step 1: Define Goal and Scope

The first step to performing an LCA is to establish the goal and scope of the assessment. This step is important because determining *why* and *how* you are conducting an LCA will help you direct your efforts and ensure that your work is meeting your goal.

## How to define the goal

There are many possible reasons for conducting an LCA of a building. The broad goal is usually to understand a building's environmental impact, but it is helpful to identify a more specific goal. Possible goals are listed below [10]:

1. Assist in decision-making:
   - To compare design options
   - To test options between multiple suppliers of similar products with different environmental impacts
   - To evaluate a building in order to identify the largest contributors to the total environmental impact (this is a 'hot-spot' analysis)
2. Declare performance with respect to legal requirements:
   - To comply with emerging regulations in Europe and Canada [13]
   - To obtain zoning variances in some jurisdictions [14]
3. Document environmental performance:
   - To achieve green building rating points, which commonly require comparing a proposed design to a reference building
   - To calculate the building's carbon footprint for purposes of carbon accounting or carbon offsets
   - To document a building's performance in order to identify which components and/or life cycle stages are the largest contributors to the total environmental impact
   - To report environmental impacts for marketing purposes

4. Support for policy development:
    - To compare the impacts of different development options for planning and zoning requirements
    - To understand the order of magnitude of impacts of building construction and identify opportunities to reduce these impacts

It is also helpful to identify your audience so that you can shape your assessment to meet their level of knowledge.

## How to define the scope

The LCA scope defines what is included in or excluded from the analysis. Since there are so many things to consider in the scope, this Practice Guide aims to provide specific guidance on what must be included in the scope.

You must define the following items under the scope:

- A *functional description* of the building
- *Reference study period*
- *System boundary,* which can be broken down into:
    - Building and site scopes, which describe the physical parts of the building and project site to be included
    - Life cycle scope, which describes the life cycle stages to be included

The following subsections describe these parts of the scope in more detail.

### *Functional equivalence*

The terms *functional equivalence* or *functional unit* are used in LCA standards to describe the key function(s) of the *object of assessment* (which in this case is a building) using a set of objective criteria. This means that you must describe your building in a way that is both meaningful to others in the building industry and rigorous enough to make comparisons in LCA. Defining a functionally equivalent building and using it consistently ensures that you are making “apples-to-apples” comparisons within your study or with other related studies.

Assessing functional equivalence may require judgment. When making comparisons in LCA, you must ensure that the options are equivalent in terms of the broad range of performance characteristics throughout a building’s full life cycle. For example, if changing enclosure materials changes operational energy consumption, the use stage must be carefully considered in order to satisfy functional equivalence.

There are many characteristics that you can report about your building. Please refer to the *Taxonomy for Whole Building LCA* document in the **Online Resources** for recommendations on how to report building characteristics in a standardized way.

### *Reference study period*

The *reference study period* is the time span, typically measured in years, that the building experiences for the purposes of the LCA. This typically affects the operational impacts of the building, such as total energy use, water use, and quantity of material replacements. In many cases, you can assume that the reference study period is the same as the building lifespan, also known as the *required service life*.

But how do you determine the building lifespan? The actual lifespan of a building is inherently uncertain due to factors such as design quality, number of owners, and redevelopment potential. Ultimately, if you are trying to follow a particular green building rating system, you should use the rating system's required service life as the LCA reference study period. Otherwise, run your model twice, once with a lifespan of 50 years and second with a lifespan of 100 years. It is good practice to vary the building lifespan and compare the effects on the results because it helps determine how dependent the results are on the lifespan of the building. This is an example of a sensitivity analysis, which is discussed more in **Step 4**.

What if the LCA reference study period and building lifespan are different? This may happen if there is a conflict between requirements in regulations, green building rating systems, and/or clients. What should you do then?

- If the RSP is longer (>) than the ReqSL, then you must assume that the building is reconstructed during the RSP and incorporate the impacts of the new building (or account for alternative end-of-life impacts during the remaining time period).
- If the RSP if shorter (<) than the ReqSL, then you must ensure that your analysis results are scaled to the RSP. See EN 15978 [10] for more information.

### *System boundary*

The system boundary describes 1) the physical scope of the building or product studied, 2) the scope of the life cycle assessment stages, and 3) impacts to be evaluated.

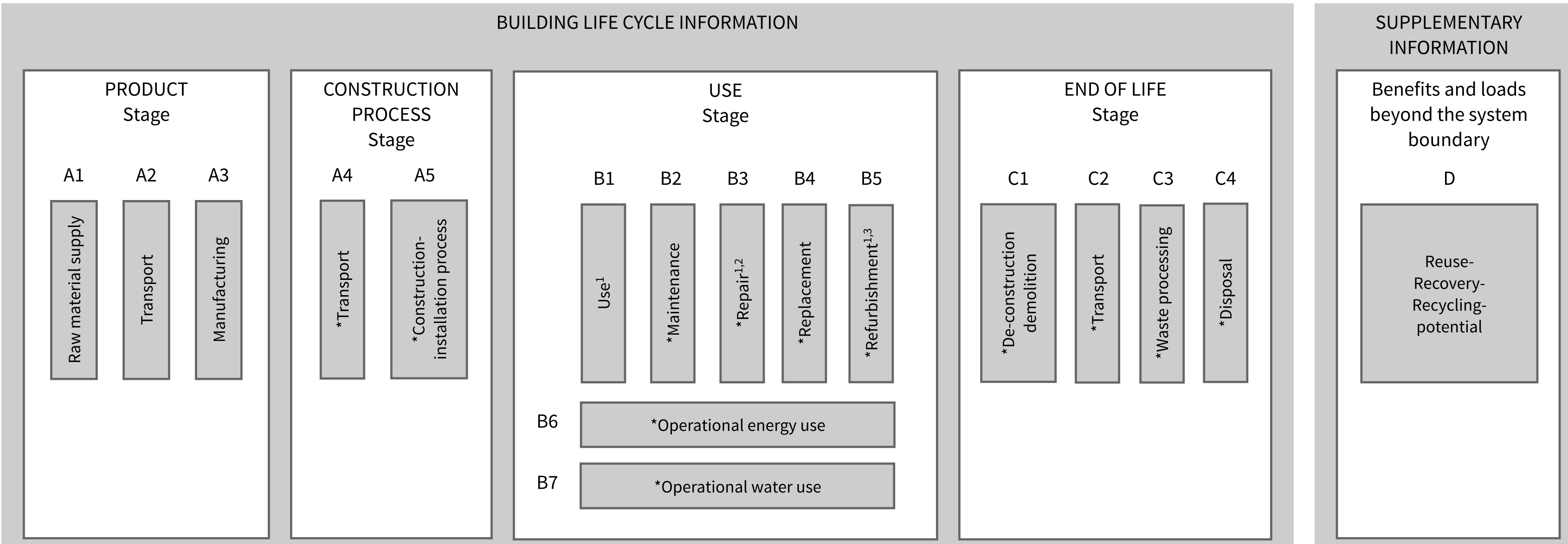
The physical scope of a whole building LCA typically includes at least the structure, enclosure, and foundations. Ideally, it should also include the impacts of building operations (electricity, fuel and water use), as well as internal finishes, furnishings, mechanical, electrical, and plumbing (MEP) systems, but these components are often excluded due to the difficulty in collecting the necessary data. The physical scope also usually excludes construction of infrastructure outside of the building (e.g. electrical transformers, roadways etc.). The *Taxonomy for Whole Building LCA* in the Online Resources contains information on how to report building scope in a systematic way. Not all LCA tools are equipped to evaluate the full building scope, which might limit the extent of your analysis.

The life cycle scope being considered in your assessment should be specified according to the standardized module designations (A1, A2, A3... through D) as shown in **Figure 4**.

Finally, at this point, you should decide which environmental impact categories you will be evaluating. Global warming potential? Embodied energy? More? This should support the goal of your study. Often, the selection of available environmental impact categories is limited by the tools or data you use. The topic of environmental impact categories is discussed further in **Step 3**.

### What constitutes a "whole building LCA"?

Whole building LCA (WBLCA) is a term that is often used to refer to LCAs of buildings. However, not all "whole" building LCAs truly encompass the "whole building" in terms of scope. Often, these assessments only include certain components, such as structure and enclosure, but exclude other significant components such as MEP, site work, or interiors. This Practice Guide encourages the inclusion of these other components into standard practice in order to realize the full environmental impacts of buildings as data, methods, and tools continue to develop.




A1: Extracting raw materials (or processing recycled materials)

A2: Transporting materials to and from the production facility

A3: Manufacturing products from raw or recycled materials

A4: Transporting products from factories to the construction site

A5: Operating equipment to install products and construct the building

B1: Effects of installed products in use, i.e. outgassing

B2: Maintaining and cleaning the building, including impacts of products used

B3: Repairing broken components, including impacts of materials and energy used

B4: Replacing building components if their lifespans are less than the building service life

B5: Refurbishing the building, including impacts of materials and energy used

B6: Using energy during normal operation of the building. Uses such as elevators, appliances and plug loads can be included

B7: Supplying and treating water for normal operation of the building[4]

C1: Deconstructing, dismantling, and/or demolishing the building, including temporary works off-site

C2: Transporting materials from the site to the end-of-waste state[5], including transportation to/from intermediate processing locations

C3: Collecting waste flows for reuse, recycling, and energy recovery. For energy recovery, see the Technical Guidance for more information

C4: Pretreating the waste and managing the disposal site

D: This module contains miscellaneous items for reuse, recycling, and recovery beyond the system boundary, such as:
- Biogenic carbon, which may be credits or burdens
- Recycling credits
- Energy that is generated on-site, exported, and/or substituted for other more common energy types

* Scenario descriptions required
[1] These modules are currently not well-supported by LCA databases and tools.
[2] Repair is defined as "returning an item to an acceptable condition by the renewal, replacement or mending of worn, damaged or degraded parts" [9].
[3] Refurbishment is defined as "modification and improvements to an existing building in order to bring it up to an acceptable condition" [9].
[4] Note that tracking operational water use is not common in whole building LCA tools and requires further development of the methodology.
[5] EN 15978 defines the end-of-waste state in Section 7.4.5.4.

**Figure 4**. Standard life cycle stages and modules, adopted from EN 15978 [10].

# Step 2: Collect Inventory

Once the project goal and scope are defined, the next step is to collect information about the building to feed into your LCA. This is much like collecting a bill of materials for a project, but more like a "bill of activities and materials" because you also need to include activities such as transportation, construction, energy consumption, water consumption, and water treatment over the full life cycle of the building. This body of information is called the *inventory*.

Collecting the inventory can be relatively straightforward or complex depending on the scope of the LCA, the complexity of the building, and the level of information already known about the project. Inventory collection may seem like a daunting task, but LCA tools can help. These tools have been designed to help estimate material quantities from templates of standard construction or BIM models. If you are using an LCA tool, it may be helpful to consult LCA tool suppliers for specific guidance on how to collect information most effectively given the organizational framework of the specific tool. A list of building-specific LCA tools can be found in the **Online Resources**.

## How to define materials

It is important to specify the types of materials or products used in your building. LCA tools often use industry average data, so be sure to note anything unusual about the materials or products you are using, especially if they deviate significantly from the industry average.

At a minimum, you will need to collect the following information regarding materials:

- Names or types of materials
- Quantities of materials (and units)
- Lifespans of materials (if applicable)
- Life cycle stage in which material is used

Most of the material quantities will appear in the production stage (modules A1 – A3), but remember to include materials and products that appear in the use stage, which covers use, maintenance, repair, replacement, and refurbishment (modules B1 - B5). If a material appears in the use stage, it will require *scenario* definitions, which are discussed next.

## How to define scenarios

Scenarios describe activities that result in environmental impacts, such as transportation details, material replacement frequencies, energy use, water use, what happens to the building at end-of-life, and the energy involved in all of these processes.  Some issues to consider include:

- What are the transportation distances for each material? What are the modes of transportation?
- Construction: What construction equipment is being used and how much energy do they consume?  How much waste is produced?
- Replacement/Refurbishment: How frequently will various products need to be replaced (or refurbished)?
- Operational energy and water use: What is the pattern of occupancy in the building?
- End-of-life: Will the building be re-purposed or demolished?  Will the material go into a landfill or be recycled?

Building industry LCA tools often integrate default scenarios within the tools, so you may not have to develop all of the scenarios yourself. Some tools enable users to modify the default values, while other tools are not as flexible. All tools should report the assumptions used in the default scenarios.

You can obtain scenario-related information from the design team, or you can use real-life data from your building.  If this information is unknown, you can consult the **Online Resources** for information on estimating scenario-related information.

Multiple types of energy sources may be involved in a single LCA of a building, depending on the material or process type and life cycle stage.  Possible energy sources include electricity, diesel, natural gas, gasoline, and various forms of renewable energy, such as solar, geothermal, or hydropower.  It is important to track each energy source separately if possible because different sources have different environmental impacts.  Even the impact of electricity depends on the regional grid mix.

### Energy: Making a comparison?

Operational energy is a significant contributor to the total environmental impact of buildings.  Comparing buildings while holding operational energy constant can be tricky, but it can be done in one of three ways (listed in order of decreasing precision):

1. Model the energy performance of the buildings using their respective construction materials and assemblies, but hold all other factors constant, e.g. location, orientation, and energy modeling method.
2. Estimate operational energy use based on design target energy use indicators (EUIs) for each building.
3. Determine that the compared buildings are functionally equivalent with regards to operational energy (ideally with the help of an energy performance professional).  If the buildings are determined to be functionally equivalent, then operational energy can be omitted from the comparison.

The level of detail of operational impacts should match the goal and level of detail of the study.

# Step 3: Perform Impact Assessment

After you have established the goal and scope of the assessment (**Step 1**) and collected data about your building (**Step 2**), the next step is to calculate the environmental impacts of your building.

In most cases, you can use software tools to do the number-crunching for you. The tools keep track of materials, scenarios, and impacts, and can organize the results by life cycle stage and building component. See the Online Resources for a current list of LCA tools and databases.

The alternative to using a tool is to perform the calculations yourself, which would likely require a spreadsheet and access to LCI databases.  It is best to only use a single source of data within an LCA because data from different LCIs are not necessarily comparable.  However, if you must use multiple sources of data, you should state your data sources clearly.  You may also use data from an *environmental product declaration* (EPD), which are product-specific LCAs produced by manufacturers.  However, like LCA tools, EPDs are not necessarily comparable, especially those that were created for different product categories, using different LCA datasets, or if they were published by different program operators.

Be sure to separate the results of the impact assessment by life cycle stage.  Separating them will help your interpretation of the results in **Step 4**.

## Which environmental impact categories should be assessed?

As first described in the **Introduction**, the five most commonly tracked environmental impact categories in LCA are:

- Global warming potential (GWP)
- Ozone depletion potential (ODP)
- Eutrophication potential (EP)
- Acidification potential (AP)
- Smog formation potential (SFP)

The science behind developing these five impact categories is well established and fairly standardized, which is why they are commonly used in LCA.  Other impact measures, such as human health impacts and ecotoxicity, are not as widely used because they have been developed with varying degrees of uncertainty.  If you are interested in assessing material health impacts, material hazard assessments would be more appropriate than LCA.

In addition to the five most common impact categories, LCA can also report material and resource consumption inventories such as water or energy use. Evolving international standards provide guidance on which LCA impacts and inventory items should be reported [11], but for most building industry professionals, these five impact categories are a good starting point.

### *Note on biogenic carbon*

If you have wood products in your project, you will likely have to deal with the issue of biogenic carbon. *Biogenic carbon* refers to carbon that is "produced in natural processes by living organisms but not fossilized or derived from fossil resources" [11]. The process of extracting carbon dioxide from the atmosphere and storing it in a long-term form is known as *carbon sequestration*. In the building industry, this most commonly occurs in wood products. Other biogenic construction materials may include bamboo, straw, and cork. Sequestered carbon can be reported as a negative carbon "emission."

Since wood is a product of removing carbon from the atmosphere, there is a perceived environmental benefit in using wood products. However, the question of how to quantify the impact of biogenic carbon is a complex and contentious issue, involving topics such as carbon neutrality, sustainable forestry certification, carbon accounting of everything in a forest including soil, and biomass burning.

For practical purposes in your LCA, you have two options for reporting biogenic carbon (at this time):

- Option 1: Ignore potential benefits of carbon sequestration. This is a conservative approach.
- Option 2: Include potential benefits of carbon sequestration.

If you chose Option 2, you should follow these additional guidelines (at this time):

- Report biogenic carbon emissions from each life cycle module for the three classifications of biogenic carbon per ISO 21930 (2017) [11].
- Report the sequestration credit as a separate negative value (not added to the positive emissions values).
- If your biogenic material is wood, report the status of forest certification.

# Step 4: Interpret Results

Once you have obtained the results of your LCA, you will want to understand them beyond the simple numbers. What do the results mean for your study? Can you have confidence in them? What conclusions can you draw? This is all part of the *interpretation* step of LCA.

After an initial overview of the LCA results, a good first step is to break down the environmental impacts by building component, material type, and/or life cycle stage, and visualize the results. This can help you get a sense of which building components, materials, and life cycle stages are significant contributors to the total building impact.

LCA is often an iterative process because 1) the quantity of data going into the analysis increases the chances of error, and 2) the results may not meet the goal of your study, which would then require you to reconsider your whole study. Additionally, you may gain more finely-grained information as the LCA progresses, which would then allow you to refine your environmental impact assessment. The interpretation step will inform you if you need to reiterate the LCA.

Three different activities can take place as a part of the interpretation step:

1. Checking for errors in the analysis
2. Understanding the results
3. Developing conclusions

These three activities lend themselves to reiterating the LCA process multiple times. An outline of this iterative process, including checkpoints showing where you would consider repeating an earlier step, is shown in **Figure 5**.

## How to check for errors

It may be difficult to find errors in your study, especially if you are new to LCA. However, here are some suggestions for possible approaches:

1. **Compare to similar LCA studies**. If you can find an LCA study of a similar building – similar in size, type, function, assemblies, etc. – you can compare the results to see if the values are in the same neighborhood. If the values are vastly different, can you understand why? Is it due to the differences

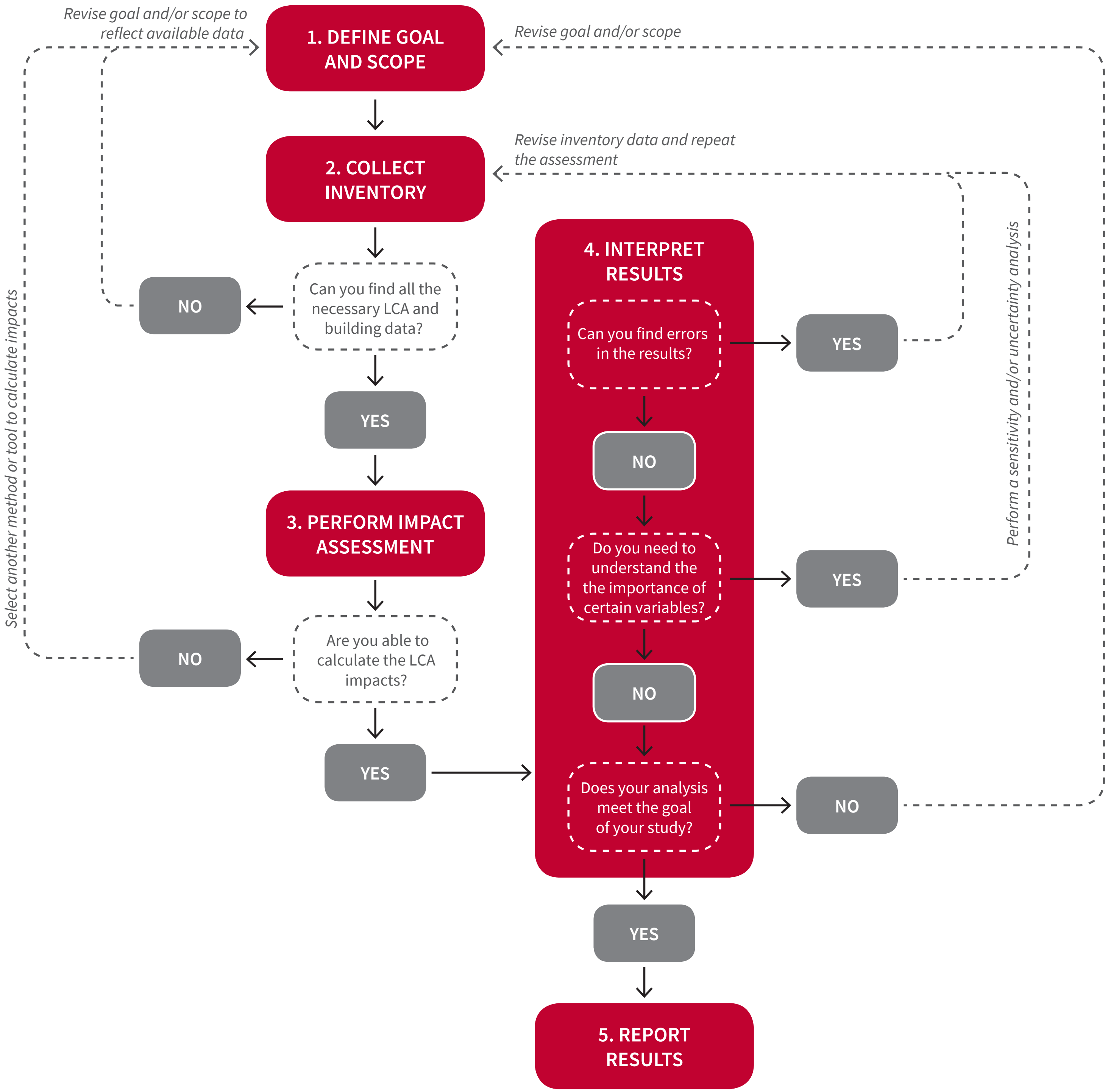



**Figure 5**. Iteration checkpoints in LCA.

between studies or a possible error in yours?

2. **Compare to the Embodied Carbon Benchmark Study**. The Embodied Carbon Benchmark Study [18] surveyed the carbon footprints of over 1000 LCA studies of buildings. One major finding of this study was that the typical embodied carbon (life cycle stage A) of a building's structure, foundation, and enclosure is typically less than 1000 kg $CO_2e/m^2$. If you calculate the carbon footprint of your building (by dividing the total global warming potential by the total floor area of the building) and find that it is greater than 1000 kg $CO_2e/m^2$, then there may be an error in your study, or you should explain why your values are unusually high.
3. **Evaluate material impacts and quantities**. There are some building materials that have notably high environmental impacts, which may help you "reality-check" your results. Do your results make sense given the material quantities and material-specific impacts? For example, aluminum and glass have high global warming potential impacts, so a building that is covered in glazing should show a significant portion of its carbon footprint due to these two materials.

If you find an error in **Step 2**, you should you should revise the inventory data and recalculate the impacts in **Step 3**. It is unlikely that Step 3 generates errors if you are using an LCA tool to perform the impact assessment, but if you performed your own calculations, you might want to double-check your work.

## How to understand the results

LCA results can initially be opaque and difficult to interpret, but there are methods that can help you better understand the data. After breaking down your building into its component parts, the next step is to take a closer look at certain variables and explore how they affect the overall results. Performing a *sensitivity analysis* or *uncertainty analysis* can help you understand how much these variables matter.

A sensitivity analysis helps identify variables in your LCA that have the greatest impacts on the results. This variable may be a physical component such as a material, assembly, or energy source; or it may be an assumption such as the required service life or reference study period. To perform the sensitivity analysis, modify the variable of interest, re-run the LCA, and evaluate the difference in results. The magnitude of change in the results can indicate how sensitive the results are to that particular variable. If tweaking a variable has a significant impact on the results, this may point towards an opportunity to reduce environmental impact. To report changes made as a result of the sensitivity analysis, you can state that you modified a certain variable from type *A* to type *B* or by *X* percent, resulting in a *Y* percent change in overall results.

An uncertainty analysis identifies which portions of your LCA are most uncertain. This matters because it affects the strength of your findings. To perform the uncertainty analysis, think about which parts of your analysis have a high level of uncertainty (this usually resides in the inventory collection). For example, perhaps the material quantity take-offs for concrete in your project were very coarse, so you could say that the level of uncertainty around concrete is very high. After identifying sources of uncertainty in your analysis, you can also perform a sensitivity analysis on the uncertain variable by experimenting with a range of possible values and evaluating the outcomes. Generally, if a prominent variable – one that is high in quantity or high in environmental impact – carries a high level of uncertainty, then you should presume that the final results also have a high level of uncertainty.

It is possible that some variables are both highly sensitive (or significant in the overall results) and highly uncertain. In that case, you would have less confidence in the overall results than if high levels of uncertainty were attributed to components of low significance.

After performing sensitivity and uncertainty analyses, be sure to include a summary of your methods and findings in the project report as described in **Step 5**.

## How to develop conclusions

Once you have a better understanding of your results, you can use this knowledge to formulate conclusions. Do your results meet the goal of your study? Depending on your goal, this can be as simple as yes or no, or it may require a more qualitative answer.

Deciding whether your results meet the goal of your study can be challenging if there are multiple impact categories to consider. Normalization and weighting can help in these cases.

### *Normalization (optional)*

The term *normalization* generally refers to the process of dividing the results by a factor in order to convert the results to a common scale. In LCA, you can divide your results by a nation's total environmental impacts to understand their significance in a national context. Normalized impacts that are relatively high can be interpreted as being more significant than impacts that are relatively low. Normalization can help you decide which impacts are more important to consider than others.

### *Weighting (optional)*

A *weighting scheme* is a set of factors that ranks the relative importance of each impact category. You can consult a weighting scheme to decide how much importance to assign to each impact category. If you want to produce a single environmental "score" from your results, you can multiply each impact with its weighting factor and sum the results to produce a single value.

Weighting is a controversial practice because it adds subjective judgment to quantitative analysis. For this reason, weighting is not commonly performed in LCAs. That being said, it should be noted that an analysis that only considers carbon or GWP takes the form of a weighting scheme that assigns 100% of the weight to carbon and zero to other impacts.

## TRACI normalization factors

In the United States, TRACI provides total US emissions in addition to characterization factors for each substance in its database [4]. The TRACI normalization factors are obtained by summing the impact of all these substances and dividing by the total US population for the reference year (2008 for TRACI 2.1) to produce the total national impact for each impact category per capita. The normalization factors are shown for the five most common impact categories in the table below:

| Impact category [units] | Normalization factor per capita |
|---|---|
| Global warming [kg CO2 eq] | 24223.71 |
| Acidification [kg SO2 eq] | 90.86 |
| Eutrophication [kg N eq] | 21.62 |
| Ozone depletion [kg CFC-11 eq] | 0.16 |
| Smog [kg O3 eq] | 1392.05 |

## Weighting schemes in the US

Weighting factors from two US weighting schemes for the five common impact categories are shown in the table below [20]:

| Impact Category | NIST BEES Stakeholder Panel | EPA Science Advisory Board |
|---|---|---|
| Global warming | 29 | 16 |
| Acidification | 3 | 5 |
| Eutrophication | 6 | 5 |
| Ozone depletion | 2 | 5 |
| Smog | 4 | 6 |
| Fossil fuel depletion | 10 | 5 |

# Step 5: Report Results

In order to communicate the results of your study, you should publish your assumptions, methodology, observations, and conclusions. Most LCA tools can produce project reports and summaries for you. At a minimum, your report should include:

- Goal and scope, including:
    - Statement of LCA goal
    - Intended audience
    - Functional equivalent description of the building
    - Reference study period
    - Description of the system boundary: physical building scope, life cycle scope, exclusions, and environmental impact categories to be assessed
- Building inventory
    - Material types, quantities, and lifespans
    - Scenario descriptions for each material, energy source, and water flow for life cycle stages A4 – C4
- Environmental impact results for each life cycle module for the impact categories identified in the goal and scope step of the LCA
- Interpretation of results
    - A narrative description of your interpretation of the results and conclusions that you were able to draw from the analysis.
    - A summary of the quantitative assessments, such as impacts by building components or categories, and sensitivity and uncertainty analyses.
    - Suggestions for improving the building design or refining the LCA.

See the *Taxonomy for Whole Building LCA* document in the Online Resources for more detailed guidance on reporting.

### What is a taxonomy and how is it related to whole building LCA?

A taxonomy is a scheme for organizing information. The term is often used to describe the classification of biological organisms, but in this context the term is used to establish a structure to facilitate consistent communication of LCA in the North American building industry. The *Taxonomy for Whole Building LCA* was developed as a part of this Practice Guide to encouraged standardized reporting of whole building LCA information.

## How to perform verification (optional)

If your LCA will be shared outside of your organization, it should undergo verification. Verification means that an outside individual or organization conducts a peer review of your LCA to verify the results. The following four key requirements should be addressed:

1. **Consistency:** Are the system boundaries and scenarios consistent with the analysis goal and scope?
2. **Data:** Is the LCA data representative of the products being evaluated? Was the data developed in conformance with ISO 21930?
3. **Scenarios:** Are the scenarios representative of practice? Are the scenarios for different products aligned (consistent with each other)?
4. **Completeness:** Does the analysis include all relevant components to meet the intentions of the described goal and scope?

In the process of review, errors and inconsistencies may be identified that will require updating the LCA and iterating through some or all of the primary steps in order to address any issues identified by the reviewer.

Unless specified by the requirements of a program or rating system, this verification can be internal (performed by someone in the same firm who is familiar with the building but did not perform the LCA) or external (a consultant). If you want to make a comparative assertion, or publicly make an "environmental claim regarding the superiority of one product versus a competing product" [9], ISO standards require that the LCA must be reviewed by an independent critical review panel. While this is rarely done for whole building LCAs and is not necessary for internal design studies, critical reviews provide a useful level of oversight for the occasions when LCAs are used for public claims of environmental performance.

# Conclusion

Conducting a life cycle assessment of a building can be a complex task, but we hope that this Practice Guide has introduced the background and methodology in an accessible way. The **Introduction** described how buildings impact the environment, how these impacts are calculated, and how LCA is used in the building industry. The **Implementation** section of the Practice Guide explained the five key steps of an LCA:

1. **Define Goal and Scope**
2. **Collect Inventory**
3. **Perform Impact Assessment**
4. **Interpret Results**
5. **Report Results**

For additional resources, such as the *Technical Guidance*, examples, a list of building-specific LCA tools, and more, please see the **Online Resources**.

As a final note, the **Road Map to Reducing Building Life Cycle Impacts**, shown in **Figure 6**, can be used a guide to understanding which key actions and milestones are appropriate for each stage of the building design process.

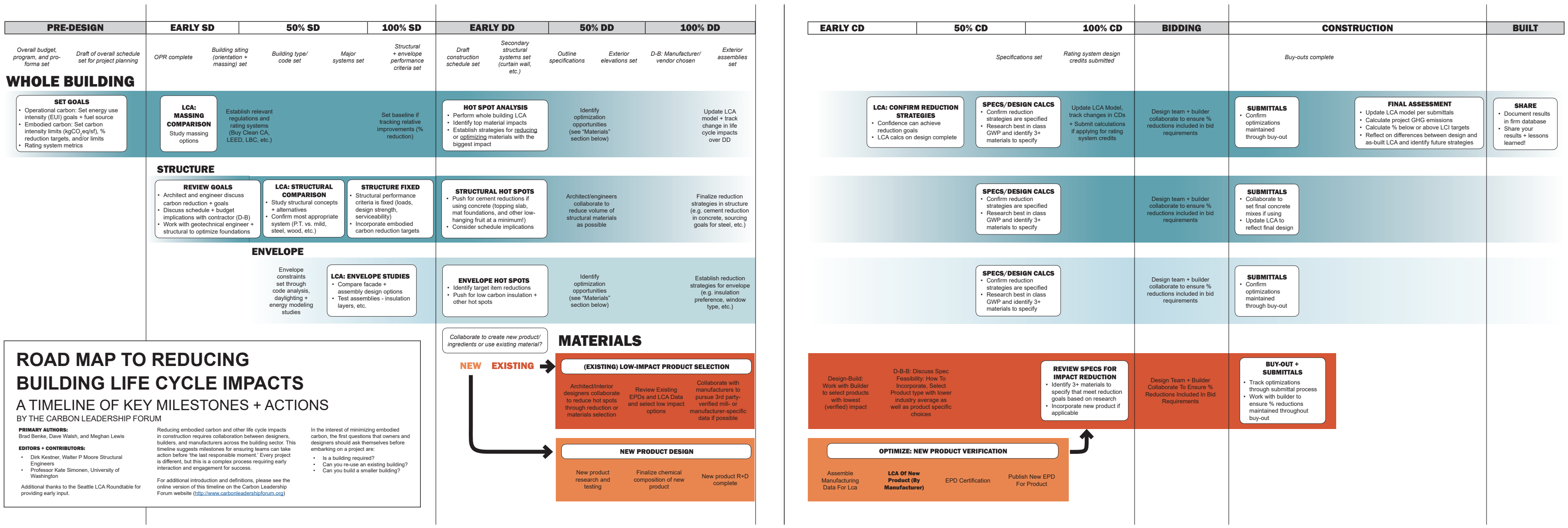



**Figure 6**. Road Map to Reducing Building Life Cycle Impacts.  See full version **here**.

# References

[1] IPCC, Summary for Policymakers. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.

[2] Architecture 2030, “Why The Building Sector? | Architecture 2030,” 2017. [Online]. Available: http://architecture2030.org/buildings_problem_why/. [Accessed: 08-Feb-2017].

[3] K. Simonen, Life cycle assessment, First. New York: Routledge, 2014.

[4] M. Ryberg, M. D. M. Vieira, M. Zgola, J. Bare, and R. K. Rosenbaum, “Updated US and Canadian normalization factors for TRACI 2.1,” Clean Technol. Environ. Policy, vol. 16, no. 2, pp. 329–339, 2014.

[5] International Association of Certified Home Inspectors, “Acid Rain and Inspectors: Buildings at Risk - InterNACHI.” [Online]. Available: https://www.nachi.org/acid-rain.htm. [Accessed: 12-Dec-2017].

[6] United Nations, Montreal Protocol on Substances that Deplete the Ozone Layer : Final act, 1987. Nairobi: UN, 1987.

[7] S. Solomon, D. J. Ivy, D. Kinnison, M. J. Mills, R. R. Neely, and A. Schmidt, “Emergence of healing in the Antarctic ozone layer,” Science (80-. )., vol. 353, no. 6296, pp. 269–274, 2016.

[8] ISO, “ISO 14040: Environmental management — Life cycle assessment — Principles and framework.” International Organization for Standardization, Geneva, Switzerland, 2006.

[9] ISO, “ISO 14044 Environmental management — Life cycle assessment — Requirements and guidelines.” International Organization for Standardization, Geneva, Switzerland, 2006.

[10] European Committee for Standardization, “EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation

method," International Standard. 2011.

[11] ISO, "ISO 21930: Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services." International Organization for Standardization, Geneva, Switzerland, 2017.

[12] American Society for Testing and Materials, "ASTM E2921-16a Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems." ASTM International, West Conshohocken, PA, 2016.

[13] R. Zizzo, J. Kyriazis, and H. Goodland, "Embodied Carbon of Buildings and Infrastructure: International Policy Review," 2017.

[14] City of Vancouver, Green Buildings Policy for Rezoning - Process and Requirements. Vancouver, BC, Canada: Planning, Urban Design and Sustainability Department, 2017.

[15] M. Bowick, J. O'Connor, and J. Meil, "Athena Guide to Whole-building LCA in Green Building Programs." Athena Sustainable Materials Institute, 2014.

[16] T. R. Miller, J. Gregory, and R. Kirchain, "Critical Issues When Comparing Whole Building & Building Product Environmental Performance," no. October. MIT Concrete Sustainability Hub, Cambridge, MA, p. 31, 2016.

[17] M. Bowick and J. O'Connor, "Carbon Footprint Benchmarking of BC Multi-Unit Residential Buildings," Ottawa, ON, 2017.

[18] K. Simonen, B. X. Rodriguez, E. McDade, and L. Strain, "Embodied Carbon Benchmark Study: LCA for Low Carbon Construction." Carbon Leadership Forum, Seattle, WA, 2017.

[19] Royal Institution of Chartered Surveyors, "Whole life carbon assessment for the built environment RICS professional statement, UK," London, 2017.

[20] B. Lippiatt, "BEES 4.0: Building for Environmental and Economic Sustainability, Technical Manual and User Guide," Gaithersburg, MD, 2007.