National guidelines for whole-building life cycle assessment

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https://doi.org/10.4224/40002740

NRC·CNRC

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National Research Council Canada
Conseil national de recherches Canada

Canada

Paper: Cat. Nº NR24-101/2022E · ISBN 978-0-660-42369-2
PDF: Cat. Nº NR24-101/2022E-PDF · ISBN 978-0-660-42368-5

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National guidelines for whole-building life cycle assessment

Abstract

This document provides comprehensive instruction for the practice of life cycle assessment applied to buildings, based on relevant standards and keyed to various intentions. The goal is to harmonize the practice of whole-building life cycle assessment (wbLCA) across different studies and assist in interpretation of and compliance with relevant standards. The guidelines will be periodically updated, as methods and standards evolve. The purpose of this document is to:

- instruct wbLCA practitioners to assure quality and comparability of their results,
- enable the calculation of reliable baselines or benchmarks,
- support LCA-based compliance schemes in green building programs and policy, and
- assist in the development and use of wbLCA software.

Acknowledgements

These guidelines were produced by the National Research Council of Canada (NRC), under the low-carbon assets through life cycle assessment (LCA^2) initiative, led by Rob Cooney (NRC). This initiative is guided by a large multi-stakeholder steering committee. Development of the Guidelines was overseen by the LCA^2 Technical Committee.

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Recommended citation:

Bowick, M., O'Connor, J., Meil, J., Salazar, J., Cooney, R. (2022). *National guidelines for whole-building life cycle assessment*. National Research Council Canada: Ottawa, ON. 112 pp.

Paper: Cat. No. NR24-101/2022-E
ISBN 978-0-660-42369-2
PDF: Cat. No. NR24-101/2022E-PDF
ISBN 978-0-660-42368-5

Également disponible en français

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Applicable terms and definitions

The following terms and definitions apply to this document. Where definitions are drawn from the standards EN 15978:2011 [1], ISO 21930:2017 [2], or ISO 21678:2020 [3], this is indicated accordingly.

Accuracy
A data-quality metric that describes the degree to which the bill of flows reflects the actual or eventual conditions on site.

Baseline
A benchmark derived from a single building; may be derived from a theoretical design or a constructed building.

Benchmark
Reference point against which comparisons can be made. (ISO 21678:2020)

Benchmarking
Process of collecting, analysing and relating performance data of comparable buildings or other constructed assets. (ISO 21678:2020)

Bill of flows
The list of all life cycle flow quantities included in the building model scope that are required to model the system boundary.

Bill of materials
The list of product flow quantities included in the building model scope that make up the physical building.

Biogenic
Produced in natural processes by living organisms, but not fossilized or derived from fossil resources. (ISO 21930:2017)

Biogenic carbon
Carbon derived from biomass. (ISO 21930:2017)

Biomass
Material of biological origin, excluding material embedded in geological formations or transformed to fossilized material, and excluding peat. (ISO 21930:2017)

Note: Biomass includes organic material (both living and dead) from above and below ground; e.g., trees, crops, grasses, tree litter, algae, animals, and waste of biological origin, such as manure.

Building model
The building design information used to derive flows for the purpose of wbLCA; e.g., a building information model (BIM), energy model, utility bill, etc.

Building model scope
The scope of building elements included in analysis; defined as the inclusion/exclusion of OmniClass Table 21 level 3 element titles.

Carbonation
A carbon dioxide reaction with cementitious products to form calcium carbonate. (ISO 21930:2017)

Completeness
A data quality metric that describes the degree to which all flow quantities within the assessment scope are included in the bill of flows.

Construction-energy flow
A quantity of energy used for construction, deconstruction or demolition activities during the building life cycle; allocated to information module A5, B2-B5 or C1.

Construction-water flow
A quantity of water used for construction, deconstruction or demolition activities during the building life cycle; allocated to information module A5, B2-B5 or C1.

Contribution analysis
The process of grouping indicator results together in different ways to better understand what is driving them.

Cradle-to-gate
Time period from resource extraction through building product manufacturing.

Cradle-to-grave
Time period from resource extraction through end of life.

Declared unit
Quantity of a construction product for use as a reference unit in an *EPD* based on *LCA*, for the expression of environmental information needed in information modules. (ISO 21930:2017)

Degree of carbonation (Dc)
Accounts for the fact that not all available calcium oxide (CaO) will react as the carbonation front moves through the concrete.

Environmental product declaration (EPD)
Environmental declaration providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information. (ISO 21930:2017)

Flow
An input (quantity of product, energy or water) or output (quantity of waste) to the system boundary over the building life cycle.

Functional equivalent
Quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison. (EN 15978:2011)

Functional requirements
The type and level of functionality of a building or assembled system which is required by the client and/or by users and/or by regulations. (EN 15978:2011)

Functional unit
Quantified performance of a product system for a construction product or construction service for use as a reference unit in an EPD based on LCA that includes all stages of the life cycle. (ISO 21930:2017)

Information module
Compilation of data to be used as a basis for an EPD, covering a unit process or a combination of unit processes that are part of the life cycle of a product. (ISO 21930:2017)

Informing building design
The process of using wbLCA results to inform decision-making during the design phase of a building project.

In-use condition
Any circumstance that can impact on the performance of a building, or a part thereof, under normal use. (ISO 21930:2017)

k-factor
Coefficient (mm/year$^{0.5}$) that describes the rate of carbonation.

Life cycle assessment (LCA)
Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. (ISO 21930:2017)

Life cycle impact assessment (LCIA)
Phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. (ISO 21930:2017)

Life cycle inventory (LCI) analysis
Phase of LCA involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. (ISO 21930:2017)

Limit value
Upper or lower acceptable performance level on a performance scale. (ISO 21678:2020)

Material use intensity (or MUI)
A list of building material use, per gross floor area; similar to energy use intensity (EUI; e.g., MJ/m^2) and water use intensity (WUI; e.g., L/m^2).

Meeting requirements
When the purpose of the assessment is to produce a wbLCA according to another party's requirements, for regulatory purposes, green building program compliance, etc.

Net calorific value
The quantity of energy produced (per unit fuel) when the water vapor produced during combustion remains a gas.

Net output flow (NF)
The difference between the recovered secondary product/fuel leaving the product system and the secondary product/fuel that was used by the system, for all relevant information modules included in the life cycle of the object of assessment.

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

Operational-energy flow
A quantity of energy used by the building during its operation; allocated to information module B6.

Operational-water flow
A quantity of water used by the building during its operation; allocated to information module B7.

Performance declaration
A publicly available wbLCA, for communications, certification, benchmarking, etc.

Performance level
Value indicating the relative performance required (or provided) for a particular attribute on a relative scale, from the level of the least (performance) to the level of the most (performance). (ISO 21678:2020)

Note: For some attributes, such as adaptability, the level may be expressed with help of criteria; e.g., an A level achieved when 80% of criteria is fulfilled, or a B level when only 60% of criteria is fulfilled. (ISO 21678:2020)

Precision
A data quality metric that describes the degree in variance that can be expected for a given method of deriving flow quantities.

Product category rules (PCR)
Set of specific rules, requirements and guidelines for developing EPDs for one or more product categories. (ISO 21930:2017)

Product flow
A quantity of building product used by the building during its life cycle; allocated to information module A1-A5, B1-B5 or C1-C4.

Program operator
Body or bodies that conduct an EPD program. (ISO 21930:2017)

Reference in-use condition
In-use condition under which the reference RSL data are valid. (ISO 21930:2017)

Reference service life (RSL)
Service life of a construction product which is known to be expected under a set of reference in-use conditions and which can form the basis for estimating the service life under other in-use conditions. (ISO 21930:2017)

Note: The RSL is described as part of the functional unit and considered in the calculation of replacements at both the construction product level and building level and refurbishment.

Reference study period
The period over which the time-dependent characteristics of the object of assessment are analyzed. (EN 15978:2011)

Reference value
Performance level on a performance scale that represents state of the art or best practice. (ISO 21678:2020)

Note: A reference value is subject to temporal changes.

Representativeness
A data quality metric that describes the i) technology coverage, ii) time period, and iii) geographical coverage a flow quantity corresponds to.

Reproducibility
A data quality metric that describes the extent to which flow quantities can be reproduced by another practitioner.

Required service life
Service life required by the client or through regulations. (EN 15978:2011)

s-factor
A coefficient (unitless) that adjusts the rate of carbonation based on the quantities of other materials that supplement Portland cement.

Scenarios
Collection of assumptions and information concerning an expected sequence of possible future events. (EN 15978:2011)

Sensitivity analysis
The process of changing a parameter in a wbLCA model and recalculating indicator results to find out its effect on the building.

Service life
Period of time after installation during which a building or facility or its component parts continues to meet the performance requirements. (ISO 21930:2017)

System boundary
Interface in the assessment between a building and its surroundings or other product systems. (EN 15978:2011)

Target value
Performance level on a performance scale that represents an objective that goes beyond the reference value. (ISO 21678:2020)

Note: Target values can follow a top-down or bottom-up approach. Also, a target value is the result of a target-setting process.

Technical requirements
The type and level of technical characteristics of construction works or an assembled system (part of works), which are required or are a consequence of the requirements made either by the client and/or by the users and/or by regulations. (EN 15978:2011)

Technosphere
Sphere or realm of human technological activity which results in a technologically modified environment. (ISO 201930:2017)

Note: Primary resources are acquired or extracted from the environment/nature (the geosphere or biosphere) into the technosphere and emissions to air, water or land are released from the technosphere into the environment.

Transport-energy flow
A quantity of energy consumed for the transport of products used by a building during its life cycle; allocated to information module A4-A5, B2-B5 or C2.

Work result
A work activity at the building site.

Waste flow
A quantity of untreated waste produced as part of a building’s life cycle. Includes waste streams that are sent for recycling, reuse, energy recovery, disposal, and incineration; allocated to any of information modules A4-A5, B2-B5 or C3-C4.

Whole-building LCA
Life cycle assessment applied to a building-related functional equivalent (a whole building, or part of a building).

Abbreviations

BIM	Building information modeling
EPD	Environmental product declaration
EUI	Energy use intensity
GFA	Gross floor area
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LOD	Level of development
MUI	Material use intensity
PCR	Product category rules
wbLCA	Whole-building life cycle assessment
WUI	Water use intensity

About this document

Intent

The purpose of this document is to improve quality and consistency in the practice of life cycle assessment (LCA) as applied to buildings (whole-building LCA, or wbLCA) and to assist in interpretation of relevant standards.

Specifically, the intent is to:

- improve standardization of wbLCA practice in order to facilitate better quality and comparability of results across different building projects,
- provide guidance tailored to different purposes of wbLCA,
- provide a framework and method to develop and use performance benchmarks,
- improve harmonization in methodology across wbLCA software tools, and
- support LCA-based compliance schemes in green building programs and policy, and facilitate monitoring of policy effectiveness.

This document provides guidelines for complying with the intent of the referenced standards. The principal referenced standards are EN 15978:2011 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method [1], and ISO 21930:2017 Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services [2]. In addition, ISO 21678:2020 Sustainability in buildings and civil engineering works – Indicators and benchmarks – Principles for the development and use of benchmarks [3] is referenced.

Users of this document should first be familiar with EN 15978 and ISO 21930 as the foundational standards for this document. This document is primarily keyed to EN 15978:2011; it clarifies the intent, fills in explanatory gaps, and provides specific instructions for meeting the intent. Users will also benefit from reading ISO 21930:2017, to gain an understanding of the scope, method and limitations related to product-level LCA data and its application to whole-building LCA.

Intended users of this document include but are not limited to:

- practitioners of wbLCA,
- policymakers, who may cite the document as a reference in procurement or other policy,
- developers of green building certification programs, standards and codes, who may cite the document as a reference, and
- developers of wbLCA software tools.

The document assumes strong familiarity with wbLCA. For readers seeking wbLCA introductory material, please see the additional resources listed in Appendix F.

Structure

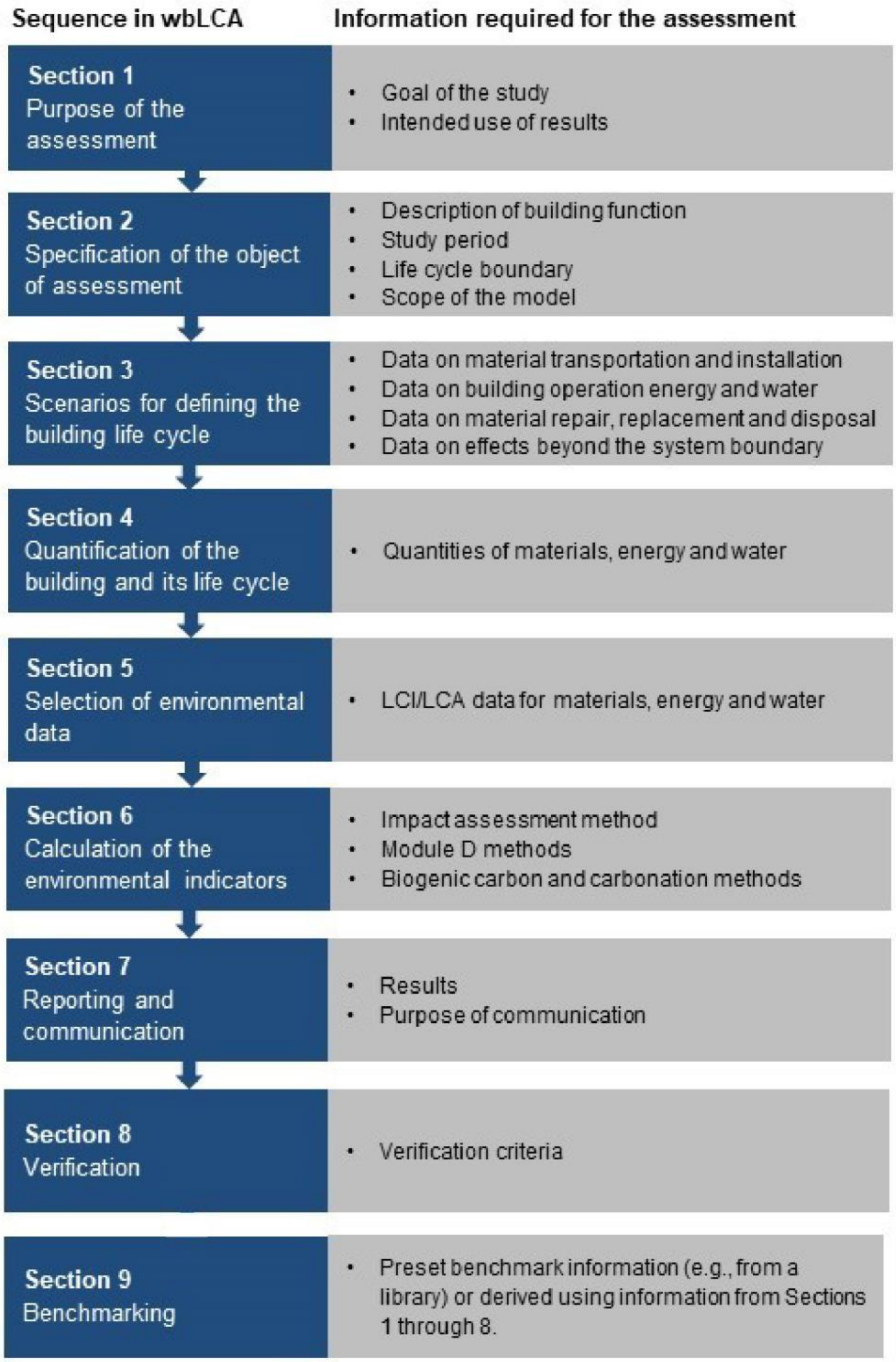
This document is organized per the sequence of wbLCA and consistent with the structure of EN 15978:2011. Sections 1 through 8 each correspond with a clause (section) in EN 15978, which also follows the order of steps taken in wbLCA. Section 9 addresses benchmarking per ISO 21678:2020, as this topic is not covered by EN 15978 but is a key consideration for most applications of wbLCA. See Figure 1 for a diagram of the structure and a list of key information inputs needed for each step.

This document provides:

- a description of pertinent provisions from relevant standards,
- guidance on the topics found in the standards,
- interpretation of the standards to fill gaps, and
- best-practice guidelines, with “should,” “shall,” and “may” statements.

Material from standards is referenced accordingly. The term “requirements” is used only in reference to instructions from standards.

“Guidance” is presented throughout this document; this is informative material providing explanations, background and help. “Guidelines” are instructions and appear in visually distinct boxes at the end of each relevant section.



Sequence in wbLCA	Information required for the assessment
Section 1 Purpose of the assessment	• Goal of the study • Intended use of results
Section 2 Specification of the object of assessment	• Description of building function • Study period • Life cycle boundary • Scope of the model
Section 3 Scenarios for defining the building life cycle	• Data on material transportation and installation • Data on building operation energy and water • Data on material repair, replacement and disposal • Data on effects beyond the system boundary
Section 4 Quantification of the building and its life cycle	• Quantities of materials, energy and water
Section 5 Selection of environmental data	• LCI/LCA data for materials, energy and water
Section 6 Calculation of the environmental indicators	• Impact assessment method • Module D methods • Biogenic carbon and carbonation methods
Section 7 Reporting and communication	• Results • Purpose of communication
Section 8 Verification	• Verification criteria
Section 9 Benchmarking	• Preset benchmark information (e.g., from a library) or derived using information from Sections 1 through 8.

Figure 1: Organization of this document

Background on referenced standards

This document addresses wbLCA as practised in accordance with the European standard EN 15978:2011. Although this is a European (not international) standard, it is internationally recognized as the most advanced document on the topic[1].

As a wbLCA standard, EN 15978:2011 references a standard related to LCA for products: EN 15804, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. This is a European standard for environmental product declarations (EPDs) of construction products. For a North American context, a different EPD standard for construction products is more relevant: ISO 21930:2017. This is because EPD practice in North America is typically in accordance with ISO 21930. Therefore, in this document, the provisions of ISO 21930:2017 are referenced in place of EN 15804, where appropriate[2].

ISO 21930:2017 contains two important updates from previous versions, and they are included in this document: biogenic carbon accounting (Section 6.3.1) and concrete carbonation (Section 6.3.2). These two factors can have a large impact on wbLCA results, but are not addressed in EN 15978:2011, as it predates ISO 21930:2017. That gap is filled here. Another gap in EN 15978 addressed here is the derivation and communication of benchmarks (Section 9), per ISO 21678:2020.

Standardization of wbLCA practice and improved comparability of results requires standardization in how materials are quantified and labeled for wbLCA model inputs. This is a key gap addressed in this document. Existing classification systems in the construction sector can be used for this purpose. The OmniClass classification system [5] is selected as the method for classifying buildings and their use of resources (materials, energy and water).

The OmniClass system is ideally suited for standardizing wbLCA model inputs. OmniClass is a collection of interlinked classification systems for buildings that provide a means to classify data in a hierarchy. Specifically, OmniClass Table 11 and OmniClass Table 12 provide a detailed way to define the project building type. Then, OmniClass characterizes product end-uses and building components, which is very helpful in wbLCA. It does this by adopting two common classification systems, UniFormat[3] and MasterFormat[4]. In this document, the components that make up the building are classified according to OmniClass Table 21 – Elements (equivalent to the UniFormat elemental classification system). Then, each element can have one or more “work results”, as classified by OmniClass Table 22 – Work Results (equivalent to the MasterFormat classification system). See Figure 2.

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[1] Another international standard, ISO 21931-1:2010 [6], may be relevant in the future and will be tracked for future revisions to this document. This standard is a framework for wbLCA and does not provide detailed instruction.

[2] EN 15804 has been updated since the publication of EN 15978; this means the references to 15804 in 15978 are out-of-date and another reason to substitute ISO 21930 here. For the most recent version of EN 15804, see [4].

[3] UniFormat is a widely used elemental classification system produced by the Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC). https://www.csiresources.org/standards/uniformat

[4] MasterFormat is a widely used classification system for specifications, organized by “trades” or “work results”. It is produced by the CSI/CSC. https://www.csiresources.org/standards/masterformat

Future updates

This document reflects wbLCA as practised in North America, based on the currently available standards. Future editions of the document will be revised when the referenced standards change and/or if new North American-specific standards emerge.

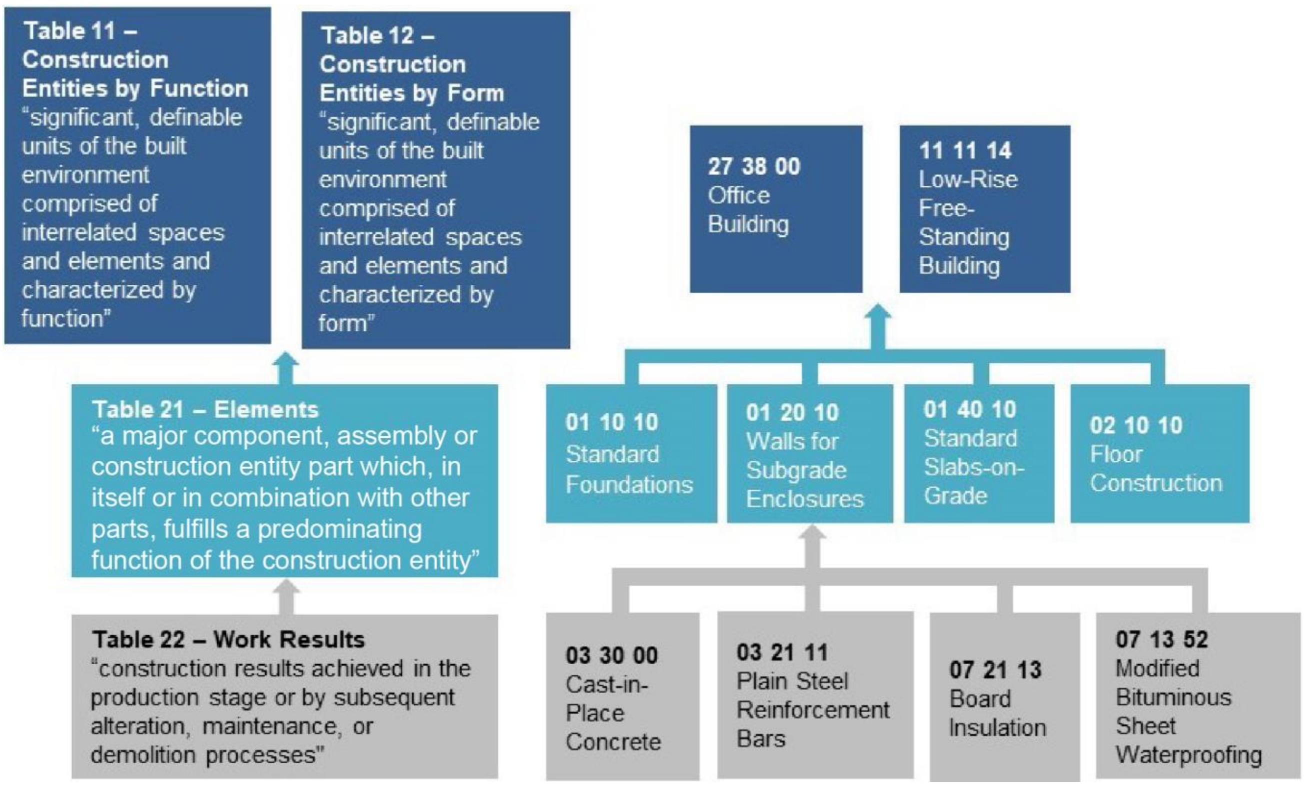

Figure 2: OmniClass system used (left) with an example (right)

1. Purpose of the assessment

EN 15978:2011 [1] Clause 6 defines the *purpose of the assessment* as a composition of the following three considerations:

a) the goal (to quantify an estimate of life cycle environmental indicators for the building),

b) the scope (addressed in Sections 2 through 6 of this document), and

c) the intended use or uses for the assessment.

The *intended use* of wbLCA results has implications for the scope and method of the assessment. EN 15978 provides no guidance on how to determine purpose or understand the implications; this section does so.

There are many applications for wbLCA. It is essential to clearly define the intended use at the start of a new project, because this characterization has significant influence on how an assessment is to be conducted. Some questions to consider when identifying an intended use include:

- What is the timing of the assessment with respect to the building life cycle; e.g., is the building new or an existing construction?
- What accuracy of indicator results are required to meet the purpose of the assessment?
- Does the assessment need to consider third-party scope or performance requirements?
- Will the wbLCA reporting be made public?

This document covers three broad uses of wbLCA with similar scope, methods and reporting needs:

a) *Informing building design.* This is the use of wbLCA results to inform decision-making during the design phase of a building project. Information is generally internal to the project team involved in a building design.

b) *Meeting third-party requirements.* This is the use of wbLCA to comply with regulatory requirements, green building programs, a request for information, etc. In some cases, information may be publicly shared.

c) *Performance declaration.* This is the use of wbLCA to provide publicly available results, for communication purposes, certification, benchmarking, etc.

1.1. Informing building design

For an intended use characterized as “informing building design,” wbLCA indicator results are used as a tool to reduce the environmental impact of a building prior to construction. A distinguishing feature of this wbLCA application is that the information available for the study changes and improves during the design process. Big fluctuations in indicator results can occur at this stage as product and system choices change and more design detail emerges.

Whole-building environmental indicator results are a function of:

a) the quantities of resources (materials, energy and water) used over the building lifetime, and

b) the impact intensities (i.e., indicator results per unit resource) of the resources used.

Therefore, the two primary tactics to reduce LCA impacts during design are 1) reduce resource use and 2) select resources with lower impact intensities (impacts per unit resource).

Comparative analyses such as those listed below can aid in design decisions. While these studies are ideally unique to each project, lessons from previous comparisons on other projects may nonetheless inform a new project.

Whole-building LCA tactics to help inform building design include:

- *Perform contribution analysis (see Section 6.4.1).* Contribution analysis is a tool to help identify the environmental "hotspots" of a building. This aids in identifying which products, energy carriers, etc. should be the focus of impact reduction strategies.
- *Perform sensitivity analysis (see Section 6.4.2).* Sensitivity analysis can be used to investigate the effect that changes in building products or systems, energy carriers, etc., and/or life cycle scenarios have on wbLCA results. This information may aid in selecting a lower impact design for the building.
- *Compare results to a benchmark (see Section 9).* Benchmarks provide the means to evaluate whether a building is meeting the desired performance level set out by the project team or to help decide the fate of an existing building.
- *Compare building new vs. refurbishing an existing building.* When the site of a new development project has an existing structure, a project team may have to decide between refurbishing the existing structure, incorporating it into the new construction, or demolishing it. These options can be assessed and incorporated into the decision-making process.

Guidance is available on design strategies to lower the life cycle impact of a building. See the additional resources in Appendix F.

When using wbLCA to inform building design, the results are typically kept internal to the project team and are not intended for public release. In this case, wbLCA can be undertaken with a lower level of detail than for other purposes. Nonetheless, care needs to be taken to ensure the scope, methods and accuracy are sufficient to draw useful conclusions.

Determining the adequacy of a study for the intended purpose is a judgement call. Experienced practitioners can draw on the findings of past work to help establish the level of assessment quality required for the types of conclusions that need to be drawn. Some questions to ask at the outset of the wbLCA work:

- What scope is sufficient to make conclusions? Can any part of the building or any life cycle activity be excluded from the analysis to streamline the process?

- What conclusions can reasonably be drawn given the available design information? For example, when schematic design options are evaluated and the differences in results are within 5%, can we reasonably conclude that the lower impact design is better? Is more design detail needed for a reliable comparison?
- What assessment accuracy is sufficient to make conclusions?

1.2. Meeting requirements

For an intended use characterized as "meeting requirements," the wbLCA is conducted to comply with a requirement from a party outside of the project team. Examples of this include:

- *Green building program:* Policy and other programs such as rating systems may require or encourage wbLCA, and this may include a performance target[5].
- *Procurement policy:* A wbLCA may be required as part of a procurement process; e.g., in a competitive bid for new construction.
- *Owner requirement:* A building owner may request that a wbLCA be performed; e.g., as part of the contract for design services.

In contrast to the flexibility allowed in wbLCA to "inform design", applying wbLCA to "meet requirements" must follow a set of rules. This is to ensure consistency, comparability and fairness. Policies or requirements based on wbLCA should therefore clearly specify detailed instruction on scope and methods for the wbLCA. Approaches that involve a performance target (a benchmark) require special considerations. This is discussed in Section 9.

The goal of assessments to "meet requirements" is typically to:

- produce a wbLCA that best reflects the building design at the time the report is submitted and/or to the quality stated in the requirements,
- produce results for an appropriate performance target, if required,
- align assessment scope and methods with the requirements, and
- produce a transparent report that communicates the requested information.

Using wbLCA to meet requirements may be the final step in a sequence of assessments that occur throughout the building's design phase. Or it may be the first step in a sequence of further wbLCA work; e.g., a schematic design wbLCA that is performed as part of a procurement process.

[5] Note that green building programs might reference the standard ASTM E2921 − 16a [31], which is not addressed in this document. This standard provides model language for wbLCA provisions in codes, standards and rating systems where a comparison to a "reference building" is required.

1.3. Performance declaration

For an intended use characterized as a "performance declaration," the wbLCA results will be publicly communicated. This may be done for the following reasons:

- as part of a communication or education strategy,
- to add the report to a building library or database, or
- to meet the reporting requirements of a building program or owner.

The key objectives for a performance declaration are to produce wbLCA indicator results with high data quality and to report the assessment as transparently as possible or reasonable. Given their use for public communication, declarations need to provide reliable, non-biased information.

The use of a reporting template is recommended, as this will aid consistency in reporting, which improves the ability to compare different declarations [23].

A similar type of performance declaration, an environmental product declaration (EPD), is not addressed by this document. If an EPD were desired for a building, this would be done in accordance with the relevant product category rules [12] and would require third-party verification.

Guidelines 1: Performance declarations	
1.1	Performance declarations shall communicate wbLCA results for a building post-design, where construction is complete or underway.
1.2	Performance declarations shall not include comparisons to other buildings or benchmarks.
1.3	Performance declarations shall demonstrate a good-faith effort to provide robust information free of bias.

2. Specification of the object of assessment

The *object of assessment* defines what is to be analyzed in the wbLCA study. According to EN 15978:2011 Clause 7.1 “the object of assessment is the building, including its foundations and external works within the curtilage of the building’s site, over the life cycle.” This section discusses how to define the object for a wbLCA study. It addresses functional equivalency, reference units, system boundaries, reference study period, and the building model scope.

2.1. Functional equivalent

Functional equivalency is an important factor in determining the comparability of results from two different wbLCA studies. In general, two buildings should be similar enough in their function that a comparison of their LCA results is fair and reasonable.

EN 15978:2011 Clause 7.2 requires that the object of assessment be adequately described to enable determination of functional equivalency for possible comparisons. This description includes the building’s design characteristics, functions, required service life, and in-use conditions.

EN 15978 also addresses the use of a reference unit to provide a common basis for comparison of wbLCA results. A whole “building” might be the reference unit, or a normalizing unit can be used, such as impacts per unit of floor area, per number of occupants, etc.

See Figure 3 for an example where three buildings are being considered for comparison. First, functional equivalency is assessed. Buildings 1 and 2 are similar in form and function and can be viewed as equivalents. Building 3 is substantially different in form and function and therefore cannot be compared to the other two. Next, a reference unit for comparing Buildings 1 and 2 is determined. Their results cannot be compared directly because these buildings are different sizes. Therefore, results are normalized to the reference unit square metre of floor area.

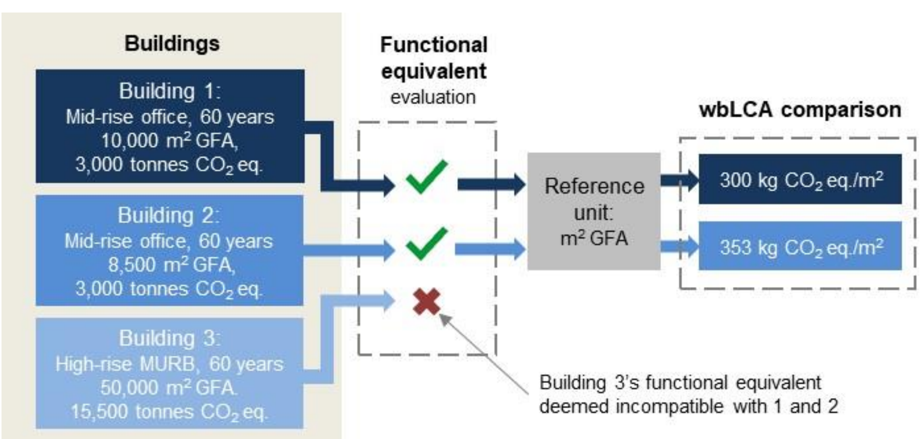

Figure 3: Example of functional equivalency and reference units

Note: GFA is gross floor area; MURB is multi-unit residential building.

According to EN 15978, building descriptive factors used to determine functional equivalency include, but are not limited to:

- *Building type*. No details for this are provided in EN 15978. Presumably, this would include a description of the primary function(s) (e.g., “commercial”) and form (e.g., “mid-rise”). This is a critical descriptor, as it addresses the basic function(s) of the building and its scale.
- *Technical requirements***.** This comprises the type and level of technical characteristics of a construction works or an assembled system (part of works), which are required or are a consequence of the requirements made either by the client and/or by the users and/or by regulations. Most of the technical requirements of a building are dictated by building codes. Other requirements may come from the building owner, rating systems, standards, local ordinances, etc.
- *Functional requirements***.** This comprises the type and level of functionality of a building or assembled system which is required by the client and/or by users and/or by regulations. This descriptor is an opportunity to provide more specific information about the functions the building provides.
- *Pattern of use***.** No details for this are provided in EN 15978. Presumably, this refers to information about the occupant relationship with the building; e.g., number of occupants, type of occupants, etc.
- *Required service life***.** This is the length of service life as required by the client or dictated by regulatory bodies. This is the period over which the building should be evaluated[6].

The degree of detail to which a functional equivalent is reported may be dependent on the intended use of the study. For example, if wbLCA results are used for public disclosure and may be subject to comparisons, a high degree of detail in functional equivalent reporting is required.

Guidelines 2: Functional equivalent	
2.1	The reported functional equivalent shall be demarcated by the following topics: building type, technical requirements, functional requirements, pattern of use, and required service life.
2.2	Building type: should be defined according to: a) a Level 3 title from OmniClass Table 11 (Construction Entities, by function), and b) at minimum, a Level 3 title from Table 12 (Construction Entities, by form). The building gross floor area in square metres, calculated according to the method in Appendix A, should be stated. For mixed-use buildings, a percent area breakdown by function may also be helpful.
2.3	Technical requirements: relevant codes, standards, policies, and green building programs that determine the technical requirements for the project should be identified. In addition, any

[6] See Section 2.4 for instructions on how to adjust wbLCA results for different reference study periods.

Guidelines 2: Functional equivalent	
	extraordinary technical requirements dictated by the building owner or occupants should be stated.
2.4	Functional requirements: a description of the building function should be provided. This may include information from the project program and building physicality where this communicates function; e.g., number of dwelling units, nature of parking provisions, etc. In addition, any extraordinary functional requirements dictated by the owner or occupants should be stated.
2.5	Pattern of use: any extraordinary patterns of use that affect the performance of the building should be reported. The number of occupants intended for the building and the manner in which that number was determined should be stated.
2.6	Required service life: should be determined according to the following general hierarchy of best practice: a) as declared by the building owner, b) the ISO 15686 series of standards [7, 8, 9, 10], c) a method required by an authority having jurisdiction, and d) other recognized standards, methods, etc. For cases in which none of the above are available, the required service life of the building should be at minimum characterized as either "permanent structure" or "temporary structure". A reference study period can then be selected on this basis.

2.2. Reference unit

A reference unit is a basis to normalize the results of a building. Building results with the same reference unit may be compared if their functional equivalents are compatible.

Floor area is a common reference unit. The following types of floor area calculations are commonly used as reference units:

- *Gross external area*: a floor area measurement taken from the outside face of the enclosing walls. In general, floor openings (e.g., for stairs, mechanical, etc.) and interior walls and structure are included. Only the lowest floors of areas that extend more than a single floor (e.g., atriums, courtyards) are counted.
- *Gross internal area*: similar to gross external area except the floor area is taken from the inside face of the enclosing walls.

- *Net floor area*: these types of area calculations further adjust the gross internal area by, for example, removing areas taken up by partitions, only accounting for particular types of spaces (e.g., usable area[7], rentable area[8]), etc.

Note that there can be different rules applied in deciding what to include or exclude (underground parking, unenclosed spaces, etc.). Consistency is important when using floor area as a reference unit for comparison.

Number of building occupants is another common reference unit that can be applied in expressing wbLCA results. Variations include:

- *Occupant loading for egress:* building codes have requirements for egress based on the design occupant load, or the number of people per-unit-area that can occupy different types of spaces. This reference unit therefore bases comparability on maximum (not average) building occupancy.
- *Occupant loading for HVAC design:* ASHRAE 62.1[9] provides occupant density calculations for ventilation; this results in a lower calculated number of occupants than building code requirements to minimize over-ventilation of interior spaces.
- *Full-time equivalents (FTEs)*: this metric is used in the LEED® suite of rating systems and is representative of average occupancy. A peak occupancy can be estimated as the FTE plus the number of transient occupants (e.g., students, visitors and customers).

Results can also be normalized on a per-year basis. This reference unit is typically used in combination with another reference unit such as floor area or occupants, because a per-year result by itself is usually not a good metric for the applications covered in this document.

The standard reference unit used in this document is gross floor area, as defined by the method provided in Appendix A. See Appendix F for a summary of common reference unit methods used in North America.

Guidelines 3: Reference units	
3.1	In general, reference units should be calculated according to a recognized methodology presented in a building code, standard or other recognized approach. The selected method(s) should be documented.
3.2	The reference unit(s) shall be selected on the basis of: a) the purpose of the study; e.g., a policy may require a particular reference unit, and b) the functional equivalent of the building; e.g., using a reference unit specific to a building type.

[7] In general, "usable area" is the portion of floor classified as tenant areas and amenity areas, with service areas excluded from the measurement.

[8] In general, "rentable area" is the sum of tenant areas and the tenant's share of amenity and service areas.

[9] ANSI/ASHRAE Standard 62.1 (various editions). *Ventilation for Acceptable Indoor Air Quality*.

2.3. System boundary

The assessment *system boundary* defines which life cycle activities are to be included in the analysis. As illustrated in Figure 4, the system boundary according to EN 15978:2011 Clause 7.4.1, is characterized by the temporal flow of the life cycle. The life cycle stage names and the alphanumeric labeling in the figure is per ISO 21930 and EN 15978. Note that the colour scheme used in Figure 4 is repeated in other figures and tables in this document, to reinforce definitions and delineations of the life cycle stages.

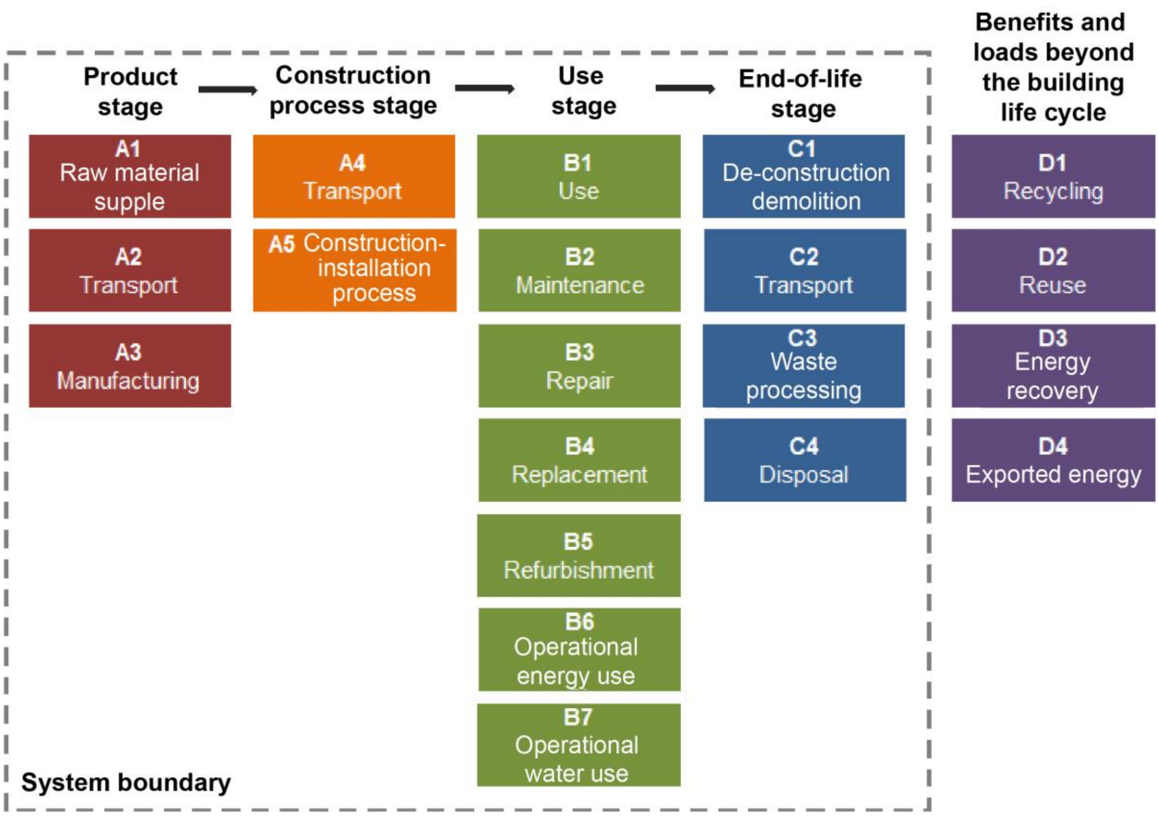

Figure 4: Assessment system boundary, per EN 15978 and ISO 21930

The timing of an assessment will affect the way the system boundary is defined. For example, if the assessment takes place at the start of the building life, all life cycle stages will be covered; if the assessment takes place during the refurbishment of a 100-year-old building, the system boundary will begin during the use phase (module B5 Refurbishment).

The activities that occur at each stage are classified and grouped in *information modules* (or simply "modules"), labeled with alphanumeric designations A1 through C4. The inclusion or exclusion of information modules when defining the system boundary depends on the purpose of the assessment and may be affected by the limited availability of scenario and/or environmental information.

Most of the information modules (A1-A5, B1-B5, C1-C4) pertain to material use. This part of the system boundary is linked to the quantity and types of products used, and how they are transported, constructed, maintained, and finally removed and processed as waste. In principle, the system boundary should include these activities for all products that make up the building and its exterior works.

Information modules B6 and B7 address the two other major types of resource use that occur over a building life cycle: operational energy and water use, respectively. These modules account for resource consumption by building-integrated operating systems. Module B6 includes the following end-uses: heating; domestic hot water supply; air conditioning (cooling, humidification, dehumidification); ventilation; lighting; and auxiliary energy used for pumps, control and automation. Module B7 includes the following end-uses: drinking water; water for sanitation; domestic hot water; irrigation of landscaped areas; water for heating, cooling, ventilation, and humidification; and water for other systems such as fountains and swimming pools.

According to EN 15978:2011 Clauses 7.4.4.7 and 7.4.4.8, other building-integrated energy or water end-uses not listed above (e.g., conveying energy, processing water) should be reported separately. Similarly, non-building-integrated energy or water end-uses (e.g., appliances, dishwashers, etc.) can be included in an assessment; however, the results should also be reported separately from the core end-uses.

Per EN 15978:2011 Clause 7.4.5.1, accounting for the building life cycle ends when:

a) all materials from the site have been cleared and have reached the system boundary between product systems[10], and

b) the site is ready for re-use.

The potential environmental benefit or burden arising from subsequent use of secondary materials and energy recovered from the system of study is optionally accounted for in module D; for example, the net benefit of a reused wood beam substituting a new manufactured wood beam. See Section 6.2 for further information.

See Appendix C for a detailed taxonomy of the specific life cycle activities that make up each information module, per EN 15978:2011 Clauses 7.4.2 through 7.4.6.

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[10] When a building is deconstructed or demolished, the materials are sorted for different end-of-life processing options; e.g., some materials, products or construction elements will be recycled, reused, landfilled, etc. As per ISO 21930:2017 Clause 7.1.6, these materials, products or construction elements reach the system boundary between product systems when all the following conditions are met:

a) the recovered material, product or construction element is commonly used for specific purposes,

b) a market or demand (identified, for example, by a positive economic value) exists for such a recovered material, product or fuel, and

c) the recovered material, product or fuel fulfils the technical requirements for the specific purposes for which it is used and meets the existing legislation and standards applicable to products or secondary fuels.

Guidelines 4: System boundary	
4.1	The system boundary of the assessment should be defined by the inclusion/exclusion of the alphanumeric activities delineated in Appendix C.
4.2	The system boundary of a “cradle-to-grave” wbLCA should include all activities noted in Appendix C for which data is available and shall at minimum include the following as described in Appendix C: A1-A3.1, A4.1, B4.1, B4.4, C2.1, C3.1, C4.1.
4.3	If the timing of the assessment (e.g., during building use) excludes information modules from the system boundary, environmental indicator results for these modules may be reported as additional information. The results may come from a previous wbLCA report for the building or be estimated using the environmental data of best quality available for those information modules. The method used should be documented.
4.4	For projects with a mix of new and existing construction, a rationale should be provided why the life cycle begins at module A1 or B5.

2.4. Reference study period

While the functional equivalent (Section 2.1) includes a definition of a building's required service life, this may not be the same as the *reference study period*, which is defined in EN 15978 Clause 7.3, as "the period over which the time dependent characteristics of the object of assessment are analyzed."

Guidelines 5: Reference study period	
5.1	The reference study period shall be selected on the basis of (in general order of preference): a) meeting the purpose of the assessment (e.g., the reference study period required by a policy), or b) the defined required service life, which is the default reference study period per EN 15978 Clause 7.3.
5.2	Where the reference study period is not the same as the required service life of the building, wbLCA results shall be adjusted per the method described in Figure 5.

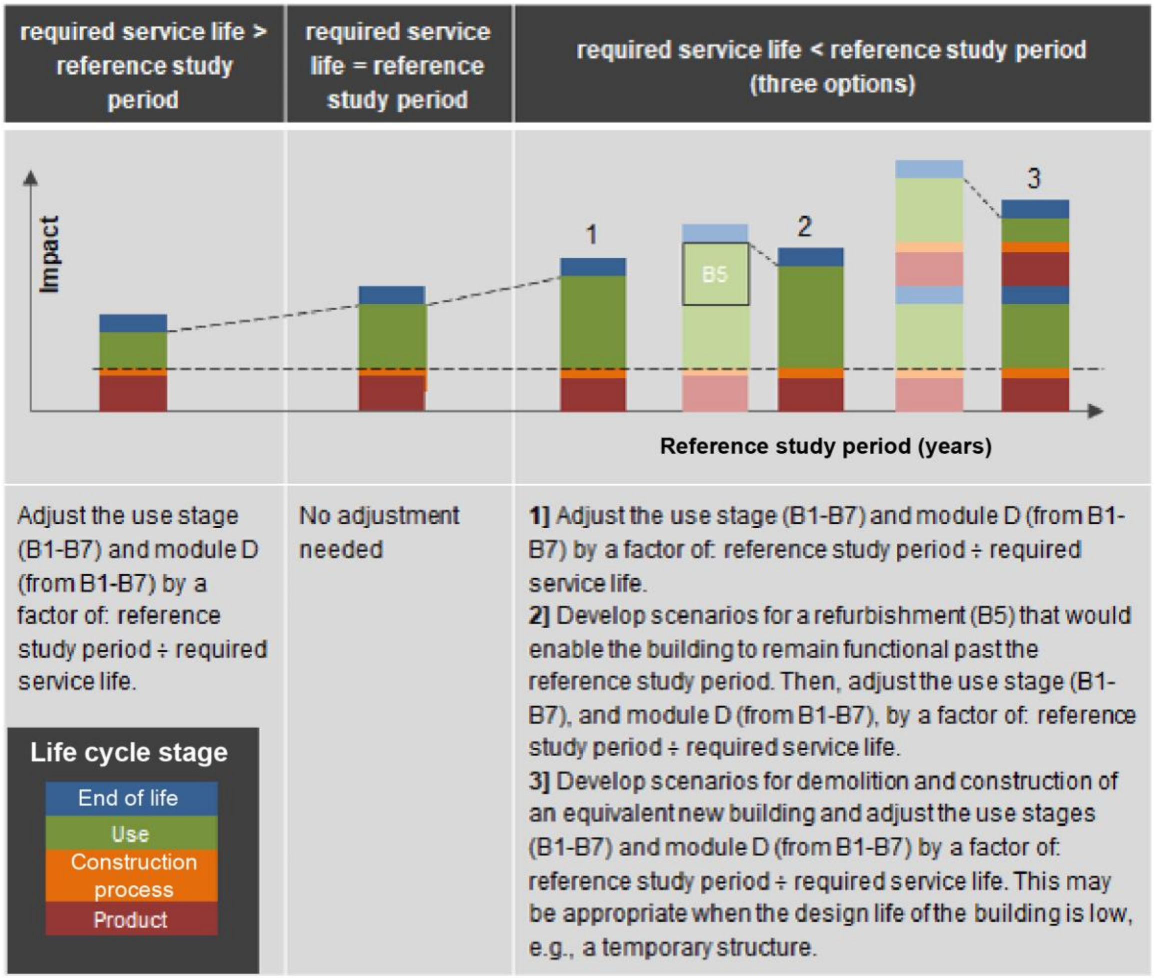

Figure 5: How to adjust results for reference study period, per EN 15978:2011 (7.3)

2.5. The building model

Not all aspects of a building can practically be addressed in an assessment; therefore, the scope of the building model needs to be clearly defined. EN 15978:2011 Clause 7.5 does not prescribe a method to do this; however, typical practice is to declare which building elements are included in the assessment.

See Appendix B for an OmniClass table with all Level 3 titles listed, which can be used as a template for this purpose. There are three columns in the table to define whether material use and/or operational energy use and/or operational water use are included in scope for any Level 3 title. This is illustrated conceptually in Figure 6. Note that it is helpful to differentiate between material, operational energy and operational water use scope since in some cases not all three of these aspects will be covered for any element. For example, the OmniClass Table 21 title “[04 30 20] Heating Systems” may be included in scope for operational energy use, but the material use of the building product that consumes the energy (e.g., a furnace) may not.

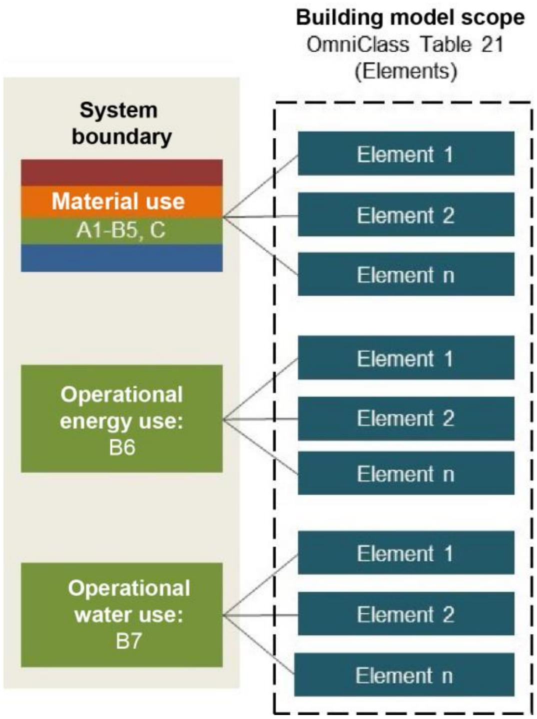

Figure 6: Defining the building model scope

Guidelines 6: Defining the scope of the building model	
6.1	The building model scope of material use, operational energy use and operational water use should each be defined by the inclusion or exclusion of OmniClass Table 21 Level 3 element titles.
6.2	All Level 3 titles within [01 00 00] Substructure, [02 00 00] Shell and [03 00 00] Interiors for which there are no applicable quantities for the bill of flows (See Section 4.2) should be noted as included in scope.

3. Scenarios for defining the building life cycle

Beyond the A1 to A3 product stage, a wbLCA needs assumptions about activities in the other life cycle stages to complete the characterization of the building. This section identifies typical scenarios (assumptions) that affect resource and emission flows over the reference study period. Sources of information and challenges with scenarios are also discussed.

See Table 1 for typical scenarios for each life cycle stage, adapted from EN 15978:2011 Clause 8.

Table 1: Summary of scenarios for defining the life cycle

Information Module	Scenarios
A1-A3 Product stage	Scenarios for these modules are locked in A1-A3 environmental datasets.
A4 Transport	Transport of materials and equipment to site and consideration of product losses.
A5 Construction-installation process	The energy and water use for initial construction, along with consideration of product losses, and ancillary materials and temporary works.
B1 Use	Emissions to the environment not covered by any other B module; e.g., substances released by a product during use. Carbonation of concrete products is a B1 effect. See Section 6.3.2 for further information on carbonation scenarios.
B2 Maintenance B3 Repair B4 Replacement	All activities associated with these period tasks, including product/energy/water use, transport and waste management.
B5 Refurbishment	All activities associated with refurbishment, including material/energy/water use, transport and waste management.
B6 Operational energy use	Energy consumption for operation of building-integrated systems, including heating, cooling, ventilation and lighting.
B7 Operational water use	Consumption of water in building operation and associated quantities sent to wastewater treatment.
C1 Deconstruction/demolition	The energy and water use for deconstruction/demolition, along with consideration of temporary works.
C2 Transport	Transport of construction waste fractions to processing or disposal.
C3 Waste processing	Waste fractions at end-of-life (generally by % of product) to various processing treatments (e.g., to recycling, to reuse, to energy recovery).
C4 Disposal	Waste fractions at end-of-life (generally by % of product) to various disposals (e.g., to landfill, incineration, etc.). Biogenic carbon accounting and concrete carbonation can be added.
D Benefits and loads beyond the system boundary	Scenarios for recycling, reuse, energy recovery, and energy export beyond the system boundary. See Section 6.2 for further information.

Scenarios are required to fill out the full life cycle, but they inherently introduce uncertainty in wbLCA results because they involve assumptions about the future. Uncertainty can be reduced if assumptions are based on data. For example, scenarios for modules A5 (construction), B5 (refurbishment) and C1 (demolition) could be confidently drawn from measured real-world data, should such data exist. A closer look at using scenarios in the wbLCA modeling process is provided in Section 4.3.

wbLCA software may allow users to input their own scenarios and/or default scenarios are applied, which are likely representative of industry averages. North American practitioners should be aware that:

- Scenarios for modules A5, B5 and C1 are difficult to characterize as they arguably require statistical analysis of many buildings. No robust studies to produce scenarios for A5 and C1 modules have occurred recently. B5 scenarios are even more difficult to characterize, and no publicly available data has been produced to date.
- Modules B2 and B3 similarly lack publicly available scenarios; however, these activities should be easier to characterize as maintenance and repair can be related to product use; e.g., a carpet needs to be vacuumed X times a week.

Guidelines 7: Scenarios	
7.1	Where available, default scenarios integrated in wbLCA software tools should be used, unless there is sufficient rationale and data resources to override them.
7.2	The use of a scenario which deviates from wbLCA software or an EPD should be documented, including the source of data, rationale for use and the method by which it was derived, if possible.
7.3	Information for scenarios should come from one or more of the following sources: a) measured real-world data, b) known project-specific information (e.g., material transport distances, client requirements), c) product-specific information produced in accordance with a recognized standard (e.g., a service life planning report in accordance with the ISO 15686 standard series, requirements per ISO 21930, etc.), d) generic third-party information applicable to the product (e.g., other databases or statistics), and/or e) product-specific information not produced in accordance with a recognized standard (e.g., information from the manufacturer, pattern of use, etc.)
7.4	If B5 is included, scenario information should come from either a refurbishment plan (in e.g., a project brief), or a scenario typical for the type of project, and be documented in reporting.
7.5	If B6 and/or B7 are included, measured data should be used where possible (if the building is already occupied); otherwise, best-practice project-specific simulation data should be used where available. Operational energy and water use may assume a constant annual demand over the use phase of the building provided other scenarios (e.g., a refurbishment scenario) do not change the demand. Modules B6 and B7 should account for any changes to the operating energy/water demand that are the result of other scenarios.

4. Quantification of the building and its life cycle

In this step of wbLCA, information is first extracted from the building model to compile a bill of materials (Section 4.1). Scenarios are applied to the bill of materials to arrive at a bill of flows (Section 4.2). The result is a list of all product, energy and water use inputs, and waste outputs over the life cycle. This section discusses quantification methods, using a framework of resource “flows” with a labeling system based on OmniClass [5]. In addition, this section addresses data sources and data quality.

4.1. Quantification of the bill of materials

Quantification of the building and its life cycle is a two-step process. The first step is to compile the project’s *bill of materials*, which is the list of product quantities that make up the physical building.

The OmniClass classification system is ideally suited for standardizing wbLCA model inputs and is therefore the recommended organizational system for bills of materials. Figure 7 shows how information derived from the building model and compiled in a bill of materials could be defined and organized according to OmniClass.

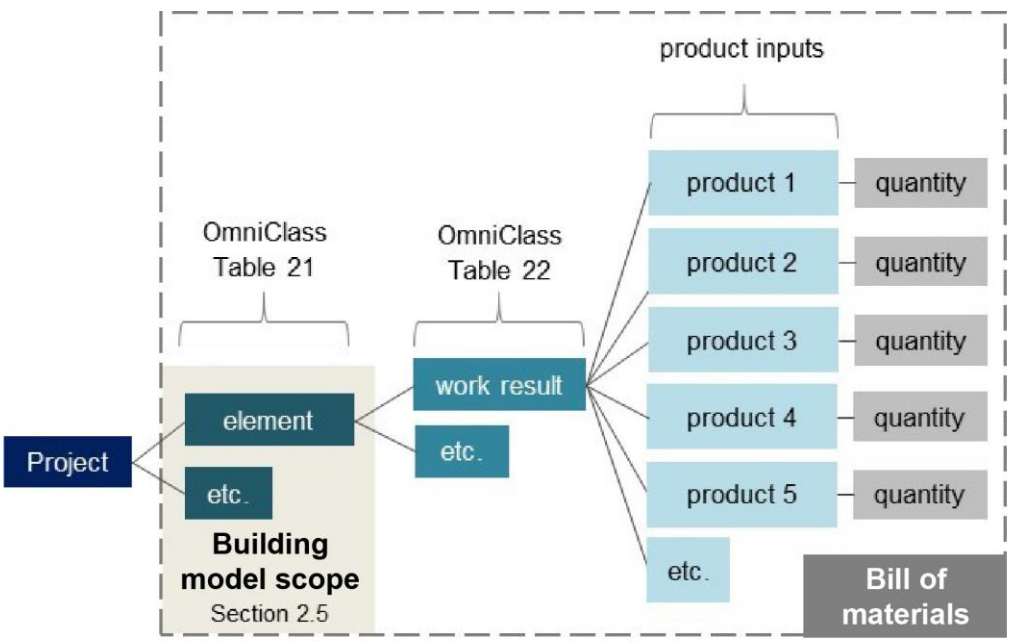

Figure 7: A bill of materials, organized per OmniClass

In this approach, the hierarchy of information is as follows:

a) A building project is made up of *elements*, as defined by OmniClass Table 21 (e.g., [01 40 10] Standard Slabs-on-Grade[11]). Elements differentiate between major components of the building and, as discussed in Section 2.5, are also the recommended way to define the scope of an assessment.

b) Each element is made up of *work results*, as defined by OmniClass Table 22 (e.g., [03 21 11] Plain Steel Reinforcement Bars). Work results are construction activity results; for example, the placement of reinforcing bars.

c) Each work result is made up of the product inputs required to achieve the construction result. For example, achieving placement of a reinforcing bar in a slab on grade requires the input of 400 MPa rebar. Each product input has a single quantity that is derived from the building model and requires, at minimum, a descriptor, which may include aspects such as material grade/type and/or thickness (e.g., carbon-steel (S) reinforcing, 40 ksi*)*, and a unit of measure (e.g., tonnes)[12]. Other metadata for product inputs such as unit density (e.g., kg product per unit of measure) and material specification reference (e.g., a CSA standard) might also be included. The type of product used, rather than particular manufacturers or suppliers, are specified, since this distinction takes place when selecting environmental data for the wbLCA (Section 5).

A completed bill of materials is achieved when all the product quantities are compiled for elements included in the building model scope.

See Table 2 for an example of a bill of materials for a single element of a building ([04 30 20] Heating Systems). In this case, the only product input is a furnace unit, which is assigned to the work result [23 54 16] Fuel-fired Furnaces. Importantly, it consumes 800 kWh/yr of electricity and 2,700 m^3/yr of natural gas (accounting for the operational energy use of the unit is addressed in Section 4.2).

Table 2: Example bill of materials, for a single element

Element	Work result	Flow	Quantity
[04 30 20] Heating Systems	[23 54 16] Fuel-fired Furnaces	*product*: natural gas furnace, 95% AFUE, 20 kW (unit)	1

The bill of materials for a project should address each element included in the building model scope in a similar way.

[11] Note that OmniClass tables are classification systems that are likewise organized as hierarchies with different "Levels". For example, [01 40 10] Standard Slabs-on-Grade is a Level 3 element of OmniClass Table 21: 01 00 00 Substructure (Level 1)→ 01 40 00 Slabs-On-Grade (Level 2)→ 01 40 10 Standard Slabs-on-Grade (Level 3).

[12] There are currently no product flow naming conventions in wbLCA other than those used internally by software. A universal approach would greatly improve consistency across wbLCA practice and would support benchmarking.

Mechanisms for obtaining product quantities include the following:

- *Building information model (BIM)***.** This 3D digital model contains data from which product quantities can be extracted. As a BIM progresses through the design phase, it becomes more reflective of what the constructed building will be. This evolution is denoted with increasingly improved *levels of development* (LODs)[13], on a rating scale of 100, 200, 300, 350, and 400. LODs are typically evaluated at the elemental scale (OmniClass Table 21). For example, a concrete foundation wall may start out as a simple generic rendering of a wall (LOD 200), then progress to incorporation of actual wall site conditions and sizing (LOD 300), then additional detail (e.g., moisture retarder) is added (LOD 350), followed by detailed reinforcing (LOD 400).
- *Cost estimate***.** Quantity surveyors and cost estimators produce cost estimates that in part rely on quantifying the product use of a building. Cost professionals use different classification systems for describing the accuracy of an estimate as the building progresses through design. See Table 3 for common methods used in Canada and the US.
- *Takeoff from drawings***.** Material quantities are manually or digitally extracted from project drawings.

Table 3: Cost estimate classifications

Canada CCA method [21]	**U.S.** ASPE method [17]	**U.S.** AACE method [34]
Class A 100% tender documents ±5 to 10%	**Level Five** bid ±0 to 5%	**Class 1** check estimate or bid/tender L: -3% to -10% H: +3% to +15%
Class B 66% design development ±10 to 15%	**Level Four** construction document ±5 to 10%	**Class 2** control or bid/tender L: -5% to -15% H: +5% to +20%
Class C 33% design development ±15 to 20%	**Level Three** design development ±15 to 25%	**Class 3** budget, authorization or control L: -10% to -20% H: +10% to +30%
Class D conceptual sketch design ±20 to 30%	**Level Two** schematic/conceptual design ±20 to 30%	**Class 4** study or feasibility L: -15% to -30% H: +20% to +50%
–	**Level One** order of magnitude ±20 to 50%	**Class 5** concept screening L: -20% to -50% H: +30% to +100%

[13] BIMForum's *2019 Level of Development (LOD) Specification Part I & Commentary* [18] provides specifications on what should be included in each LOD, for each UniFormat/OmniClass element.

No matter the method used to obtain product quantities, producing consistent and reliable information can be a challenge[14]. This is particularly an issue when datasets are mixed; e.g., within a building sample set being used to produce a benchmark. Some of these data quality issues are addressed in Section 4.3.

Guidelines 8: Quantification of the bill of materials	
8.1	The bill of materials shall be a list of the product quantities included in the building model scope that make up the physical building and its curtilage. It should not include additional material usage due to wastage; materials lost during transport or construction, etc.; or other material usage from the use stage (e.g., material replacements).
8.2	Products in a bill of materials should by default be named according to a standard convention (e.g., those used by wbLCA software) and include the unit of measure. When proxy environmental datasets are used, products should be named based on the actual product used in the building.
8.3	Each product quantity in the bill of materials should be assigned a Level 3 element from OmniClass Table 21 and a Level 3 work result from OmniClass Table 22. Quantities of the same product, with the same element and work result assigned, may be summed.

4.2. Quantification of the bill of flows

The product inputs that form the bill of materials discussed in Section 4.1 are a type of *flow*. Flows are the inputs of resources (product, energy or water) and outputs of waste, secondary materials and exported energy that occur over a building's life cycle. See Table 4 for a summary of building-related flows that are addressed in this document.

Table 4: Types of building-related flows in bills of flows

Flow types	Default unit	Description
Material use – modules A, B1-B5, C, D		
product	m^3, tonnes, etc.	Building product *input* to a building.
transport-energy	MJ, t*km, L, etc.	Energy *input* for transport of products, equipment and waste, throughout the building life cycle.
construction-energy	MJ, L, kWh, etc.	Energy *input* for equipment (for construction, maintenance and deconstruction/demolition) throughout the building life cycle.
construction-water	m^3	Water *input* for construction, maintenance and deconstruction/demolition activities throughout the building life cycle.
construction-wastewater	m^3	Wastewater *output* from construction-water. Describes a result for the wastewater; e.g., to treatment plant.

[14] Practitioners new to material quantity takeoff may benefit from the instruction provided by the American Society of Professional Estimators' *Standard Estimating Practice* [17], which provides guidance for each MasterFormat division.

Flow types	Default unit	Description
waste	kg	Waste *output* from products. Describe a result for the waste; e.g., to landfill, to incineration, to reuse, to recycling, to energy recovery.
net output flow	kg	Net *output* of secondary product added to, or taken from, the technosphere for recycling, reuse or energy recovery, after end-of-life. Used in the calculation of module D – see Section 6.2.
Operational energy use – module B6		
operational-energy	MJ, L, kWh, etc.	Energy *input* for operation of the building during the use phase.
exported energy	MJ	Net operational energy *output* (i.e., exported) from the building. Used in the calculation of module D – see Section 6.2.
Operational water use – module B7		
operational-water	m^3	Water *input* for operation of the building during the use phase.
operational-wastewater	m^3	Wastewater *output* from operational water. Describes a result for the wastewater; e.g., to treatment plant.

The second step of quantifying the building and its life cycle is to compile the building's *bill of flows*, which is a list of all flow quantities included in building model scope required to model the system boundary. Similar to a bill of materials, it is recommended that the bills of flows be structured according to OmniClass Tables 21 and 22. Flows also need to be classified by the information module they pertain to – this is crucial for subsequent selection of environmental data (Section 5) and calculation of the environmental indicators (Section 6). Finally, an important aspect of a bill of flows is its time-dependence – if the building's required service life and/or reference study period change, so do use stage quantities (modules B1-B7) of the bill of flows.

There are three broad methods for calculating flows.

Method 1: **Bill of flow quantities are derived from a bill of materials quantity using scenarios**.

See Figure 8 for an illustration of how a single product quantity from the bill of materials is translated to the various associated flows that occur over the course of the building life cycle. If we assume this product is a quantity of glazing unit (in m^2), we can observe that scenarios are applied to arrive at all flows that occur over its life cycle. Product inputs of glazing occur at initial construction (A1-A3) with on-site losses allocated to module A5; additional product inputs of glazing are required to repair damaged/faulty units (B3) and replace units that have reached the end of their service life (B4) over the course of the use stage. Installation and removal of the glazing units requires a crane and thus quantities of diesel (a construction-energy flow) are derived and assigned to modules A5, B3, B4, and C1. During initial construction, the crane is also assumed to need to be cleaned and an input of construction-water is assigned to module A5. Each time new glazing units are transported to site (A4, A5, B2, B4), and waste is removed from site (A5, B3, B4, C2), transport-energy flows occur. Finally, each time glazing units are removed from site they are landfilled and therefore waste flows are derived and assigned to modules A5, B3, B4, and C4.

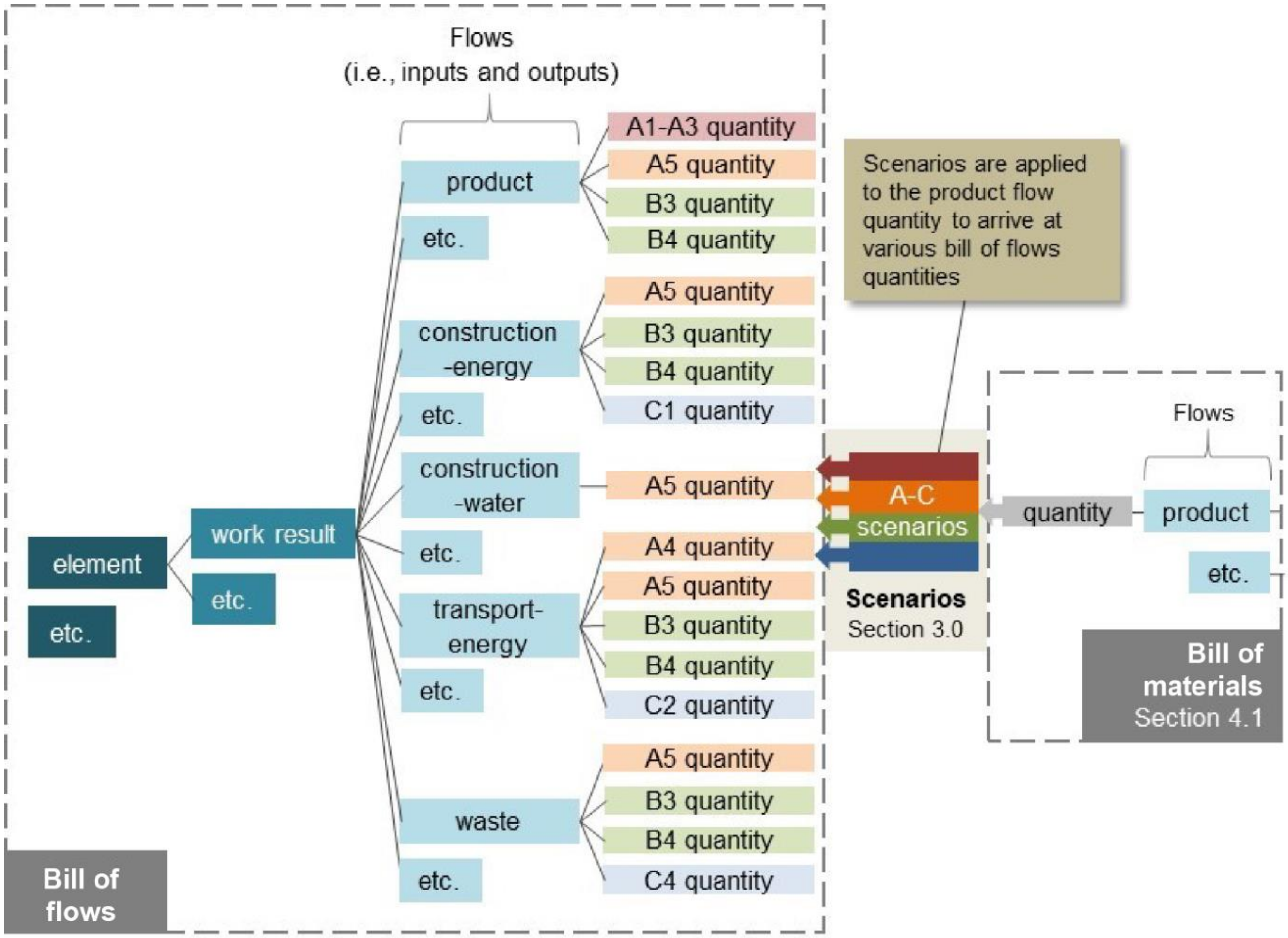

Figure 8: Bill of flows quantities derived from the bill of materials using scenarios (Method 1)

Method 2: **A bill of flows quantity comes from a scenario derived from the building model**.

What distinguishes Method 2 from Method 1 is that the flow quantity comes directly from a scenario rather than being derived with information from the bill of materials. See Figure 9 for an illustration of this method applied to operational energy and water use. Consider a case where the practitioner has derived annual operational energy use from simulation software, and annual operational water use and wastewater generation based on the building's fixtures and anticipated pattern of use. A constant-demand scenario for the building's required service life is then assumed; the resulting total operational-energy inputs are assigned to module B6, and total operational-water inputs and operational-wastewater outputs are assigned to module B7. Another common example of the application of Method 2 is construction energy use estimates; e.g., from utility bills.

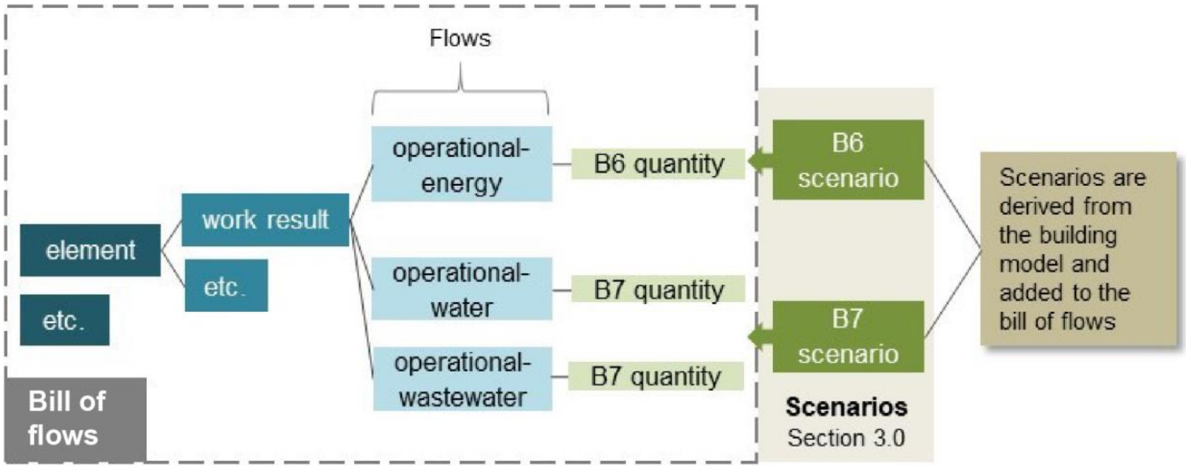

Figure 9: Bill of flows quantities from scenarios derived from the building model (Method 2)

Method 3: **A bill of flows quantity from the bill of materials is assigned modules "A-C".**

Methods 1 and 2 involve calculating quantities of inputs and outputs that occur over the life cycle. Method 3 is for cases when these calculations are essentially "baked in" to the environmental dataset that is to be used for a product found in the bill of materials. In other words, the environmental dataset to be used already accounts for the life cycle via scenarios. In these cases, the product quantity from the bill of materials is simply transferred to the bill of flows and assigned the modules "A-C" – see Figure 10 for an illustration of this. Consider again the glazing unit example described for Method 1. Instead of calculating all the life cycle flows, it is known that an EPD covering all modules (A-C) will be used, which accounts for these flows in the reported results. Method 3 will become clearer in Section 5.1 when the selection of environmental datasets is covered.

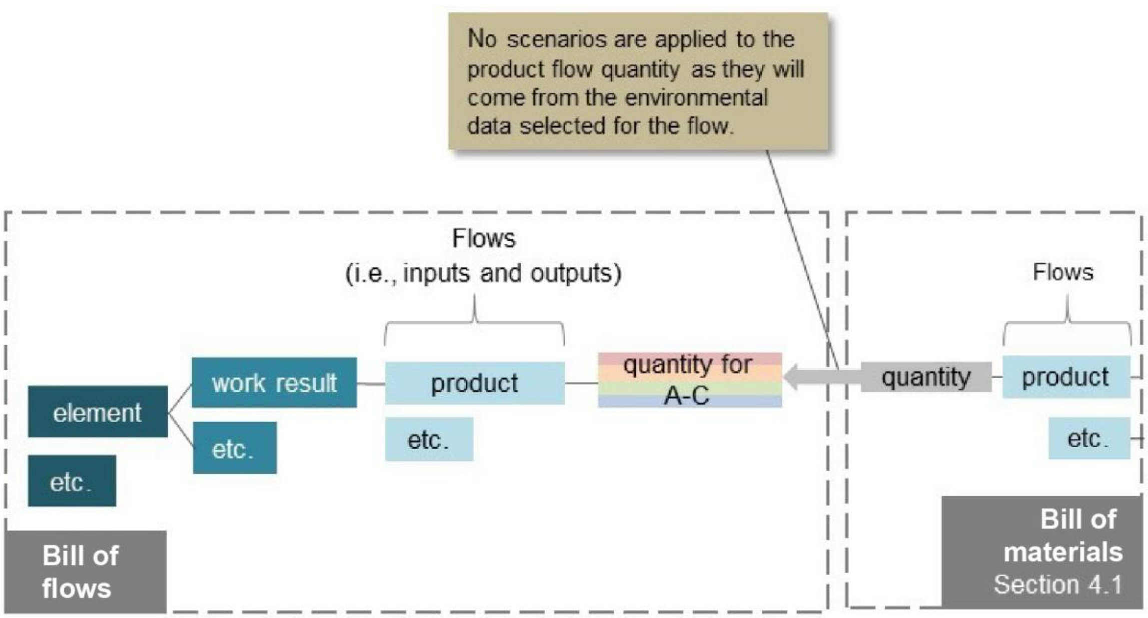

Figure 10: A bill of flows quantity from the bill of materials is assigned modules "A-C" (Method 3)

Flows of products, energy, water, and waste are accumulated as the building use phase progresses. To calculate this, EN 15978:2011 Clause 7.3 requires modeling the use phase of the building according to its required service life and adjusting the life cycle as necessary to meet the reference study period requirements (see Section 2.4).

Module B1 accounts for emissions to materials (e.g., carbon uptake from carbonation) and from materials (e.g., off-gassing); therefore, the flow quantity is simply the amount of product contained in the building.

Modules B2 through B4 usually involve scenarios of repeating activities, so the number of times activities occur over the required service life must be defined for each product. See Equations 1, 2 and 3 for calculating product flow quantities during the use phase.

Equation 1: Calculating number of times an activity occurs over the required service life, per EN 15978

$$N_x = H\,[ReqSL / F_x - 1]$$

where,

H […]	is a function that rounds up a value to the higher integer
N_x	is the number of times activity x occurs
ReqSL	is the required service life of the building (years)
F_x	is the frequency for activity x (years)

Note for Equation 1: This is how the number of activities are calculated in accordance with EN 15978. Per EN 15978 Clause 9.3.3, if the remaining service life is short in proportion to the estimated task frequency, the actual likelihood of the replacement shall take into account the required technical and functional performance of the product.

Equation 2: Calculating number of times an activity occurs over the required service life, alternative method

$$N_x = (ReqSL - F_x) / F_x$$

where,

N_x	is the number of times activity x occurs
ReqSL	is the required service life of the building (years)
F_x	is the frequency for activity x (years)

Note for Equation 2: This is an alternative method used by some wbLCA software which typically results in only a percentage of the final activity being allotted to the building.

Equation 3: Calculating the total product quantities replaced over the required service life

$$Q_{x,y} = N_x \times P_y \times P_{x,y}$$

where,

$Q_{x,y}$ is the total quantity of product y replaced due to activity x

N_x is the number of times activity x occurs

P_y is the quantity of product y in the physical building

$P_{x,y}$ is the percent of P_y replaced due to activity x

Average scenario data for refurbishment (B5) may be difficult to obtain; however, two wbLCA cases may require quantification of life cycle product flows:

- if the assessment takes place during a refurbishment; in this case, there will be good information to draw on, or
- if there is a scheduled refurbishment for the building with a plan; in this case, there should be some information to estimate quantities.

Methods for estimating operational energy and water are not addressed in this document, as these activities are well-addressed elsewhere in relevant professional resources. EN 15978:2011 Clause 8.6.5 references another European standard (EN 15603:2008 [11]) for operational energy use (B6) scenarios. Until international consensus for module B6 and B7 scenarios is reached, it is reasonable to use operational energy and water flow quantities from the bill of flows and assume business-as-usual consumption over the use phase. If a refurbishment takes place over the reference study period, any changes to operational energy and water should be accounted for, in the year it takes place.

See Table 5 for an example of a bill of flows derived using a combination of Method 1 and 2. This is a 60-year bill of flows for the residential furnace example from the previous section (Table 2). The majority of the life cycle flows are related to material use (A1-B5, C), and are derived by taking the product flow from the bill of materials (one furnace unit) and applying scenarios to it (Method 1). In this process, new flows are assessed, including transport-energy, construction-energy, construction-water (in this example considered null), product use due to replacing the furnace during the building's use phase, and the relevant waste flows at end-of-life. These flows are used to calculate what is sometimes identified as the "embodied" component of environmental indicators.

The operational energy quantities (B6) over 60 years of furnace operation come from scenarios (Method 2), and assume a business-as-usual consumption; e.g., the energy demands do not change, the technology does not change, etc. Operational water (B7) in this case is considered negligible. Note that in going from a bill of materials (Table 2) to a 60-year bill of flows (Table 5), the number of flows for this work result increases from 1 to 26.

Table 5: Example work result from a 60-year bill of flows

Module	Flow (unit)	Quantity	Scenario
Element: *[21 04 30 20] Heating Systems*			
Work Result: *[22 23 54 16] Fuel-fired Furnaces*			
A1-A3	*product*: natural gas furnace, 95% AFUE, 20 kW (unit)	1	use 1 furnace (75 kg)
A4	*transport-energy*: truck, diesel (t*km)	7.5	transport furnace to site (100 km)
	transport-energy: truck, diesel (t*km)	0.0375	transport loss (100 km)
	product: natural gas furnace, 95% AFUE, 20 kW (unit)	0.005	loss (0.5%)
	transport-energy: truck, diesel (t*km)	0.015	transport waste (30 km)
	waste: mixed metals**,** to recycling (kg)	0.5	waste processing, recycling (100%)
A5[a]	*transport-energy*: truck, diesel (t*km)	0.075	transport loss (100 km)
	product: natural gas furnace, 95% AFUE, 20 kW (unit)	0.01	loss (1%)
	transport-energy: truck, diesel (t*km)	0.023	transport waste (30 km)
	waste: mixed metals**,** to recycling (kg)	0.75	waste processing, recycling (100%)
B1	none		
B2	*transport-energy*: truck, diesel (t*km)	42	transport filters to site (350 km)
	product: furnace filters (kg)	120	maintenance activities (2 kg filters per year)
	waste: inert waste**,** to landfill (kg)	120	disposal, landfill (100%)
	transport-energy: truck, diesel (t*km)	3.6	transport waste (30 km)
B3	*transport-energy*: truck, diesel (t*km)	0.3	transport furnace to site
	product: natural gas furnace, 95% AFUE, 20 kW (unit)	0.04	replacement of parts due to breakdowns equivalent to loss (2% every 20 years)
	transport-energy: truck, diesel (t*km)	0.09	transport waste (30 km)
	waste: mixed metals**,** to recycling (kg)	3	waste processing, recycling (100%)
B4	*energy*: truck, diesel (t*km)	15	transport to site
	product: natural gas furnace, 95% AFUE, 20 kW (unit)	2	furnace replacement (20-year service life)
	transport-energy: truck, diesel (t*km)	4.5	transport waste (30 km)
	waste: mixed metals**,** to recycling (kg)	150	waste processing, recycling (100%)
B5	none, n/a		
B6	*operational-energy*: electricity, from grid (kWh)	48,000	furnace operational energy, business-as-usual, 800 kWh/yr
	operational-energy: natural gas, from pipeline (m^3)	162,000	furnace operational energy, business-as-usual, 2,700 m^3/yr
B7[a]	none		
C1[a]	none		
C2	*transport-energy*: truck, diesel (t*km)	2.25	transport waste (30 km)
C3	*waste*: mixed metals**,** to recycling (kg)	75	waste processing, recycling (100%)
C4	none		

[a] No significant construction/deconstruction energy or water use assumed for this product.

Guidelines 9: Quantification of the bill of flows	
9.1	The bill of flows shall be a list of the flow quantities included in building model scope that are required to model the system boundary.
9.2	Flows should by default be named according to a standard convention (e.g., those used by a wbLCA software) and include the unit of measure.
9.3	Each quantity in the bill of flows shall be assigned an information module, and when possible should be assigned a Level 3 element from OmniClass Table 21 and a Level 3 work result from OmniClass Table 22. Quantities of the same flow, with the same module, element and work result assigned, may be summed.
9.4	The number of times a repeating activity occurs over the required service life of the building (e.g., the periodic replacement of glazing units) may be calculated with either Equation 1 or 2. The selected method should be reported unless it is documented in the literature of wbLCA software that is referenced in the report.
9.5	The product, waste and net output flow quantities of temporary works and ancillary materials that are reused may be divided by the number of uses. Note that this does not apply to associated transport-energy, construction-energy, construction-water, and construction-wastewater flows.

4.3. Data quality of life cycle flows

The practice of wbLCA is a scientifically based estimation which relies on data drawn from multiple and disparate sources. For confidence in wbLCA results, it is the responsibility of the assessor to compile a bill of flows of sufficient quality for the stated purpose of the assessment.

There are many factors that influence which types of data will be selected for an assessment, each of which has a data quality characterization. According to EN 15978:2011 Clause 9.4.1, the choice of scenario and flow data for an assessment depends on the following four factors.

a) *The scope and intended use of an assessment***.** The choice of system boundary and building model scope determines which scenarios and flows need to be compiled. The intended use of an assessment helps establish general data quality needs; e.g., assessments that are internal to an organization will not generally require the same quality of data as an assessment that is publicly available. If a benchmark is being evaluated, the bill of materials may be based on secondary sources (databases, libraries).

b) *Timing of the assessment***.** The point in time during the decision-making process for the project (e.g., design development, construction, etc.) when the wbLCA is conducted will help determine: which information modules are to be included in scope, which affects inclusion/exclusion of scenarios and flows; whether data for certain scenarios can come from primary sources; the quality of building model (e.g. BIMs, drawings, etc.) available to derive flow quantities; and the types of intended uses available to the assessor, which influences the required accuracy of flow quantities.

c) *Availability of information*. The timing of assessment or general lack of data availability may influence how certain scenarios or flows are quantified. For example, if a wood truss roof has not yet been designed, industry-average product quantities for trusses may be used for this purpose.

d) *Relative importance*. The significance of a scenario or flow to the total building indicator results influences its data quality needs. For example, the data quality of a product that contributes significantly to the whole-building results is scrutinized more carefully than a product that contributes little.

To better characterize the data quality of flows and scenarios, the following five descriptors are drawn from the LCA standard ISO 14044 (Clause 4.2.3.6.2), which collectively aid in assessing whether data quality is sufficient for the purpose of a wbLCA:

a) *Completeness*: the degree to which all flow quantities within the assessment scope are included in the bill of flows.

b) *Precision*: the degree in variance that can be expected for a given method of deriving flow quantities. The precision of flow quantification can range from essentially perfect (e.g., actual consumption data) to less precise (e.g., estimates or data derived from an error-prone collection process).

c) *Representativeness*: a qualitative assessment of the i) technology coverage, ii) time period, and iii) geographical coverage to which a flow quantity corresponds.

d) *Consistency*: a qualitative assessment of the degree to which data quality parameters are consistently applied across, for example, different flow types, elements, information modules, etc.

e) *Reproducibility*: a qualitative description of the extent to which the data can be reproduced by another practitioner. Reproducibility is assisted by transparently reporting the flows and the manner by which they were derived from the building model.

When compiling a bill of flows, the assessor is concerned with the accuracy of the flow quantities derived from the building model. In this context, *accuracy* is the degree to which the bill of flows reflects the actual or eventual conditions on site. Accuracy is primarily affected by i) the timing of the assessment and availability of information (e.g., schematic vs. construction document phase), ii) the completeness of quantification, and iii) the precision of the quantities.

A distinct aspect of wbLCA is the long and complicated design process and service life for buildings. This creates various data quality issues. For example, wbLCA is often used during the design phase, when the detail available for the building model may be anywhere within a wide range. A wbLCA can only be as accurate as the information it is based on; therefore, the assessor factors this in when defining the purpose of an assessment, since the accuracy of the flow quantities might otherwise be insufficient. During early phases of design, not all detailing has occurred and there may be significant changes to come, so flows are generally not very accurate. By the time a building has been completed, accuracy may become an issue of completeness and/or precision, both of which the assessor can control.

Guidelines 10: Data quality of life cycle flows	
10.1	The attention to the quality of the life cycle flow quantities should be in accordance with the scope and purpose of the study.
10.2	The source of flow quantities should be classified according to the following options: a) primary: measured flows; e.g., product flow quantities from vendor bills, energy flows from utility bills, b) project-specific: flow quantities derived (extracted, calculated, etc.) from building information; e.g., product flow quantities extracted from BIMs or derived from construction drawings, energy flows calculated via simulation, etc., c) product-specific: flow/scenario data taken from product information such as EPDs and LCAs; e.g., product transport distance(s) and mode(s), and d) secondary: industry-average flow/scenario data, generally from databases, libraries, etc. Note: While these different data sources imply a scale of data quality, this may not always be the case. 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. See Appendix C for the classification of each flow in the system boundary.
10.3	The completeness of a bill of materials or a bill of flows may be considered high when the following procedure for the exclusion and inclusion of flows has been followed: a) All flows/scenarios are included for which data are available. Data gaps are filled by conservative assumptions with average, generic or proxy data. Any assumptions for such choices shall be documented. b) In cases of insufficient data or data gaps, cut-off criteria of 1% of renewable primary resource (energy), 1% nonrenewable primary resource (energy) usage, 1% of the total mass input of the building, and 1% of environmental impacts of the building are followed. The total of neglected flows/scenarios per module is a maximum of 5% of energy usage, mass and environmental impacts. When assumptions are used in combination with plausibility considerations and expert judgement to demonstrate compliance with these criteria, the assumptions are conservative. c) All substances with hazardous and toxic properties that can be of concern for human health and/or the environment are identified and declared according to normative requirements in standards or regulation applicable in the market for which the wbLCA is valid, even though the given process unit is under the cut-off criterion of 1% of the total mass. Note: This is an interpretation of ISO 21930:2017 Clause 7.1.8. Note: U.S. EPA definitions for hazardous waste can be found at https://www.epa.gov/hw/defining-hazardous-waste-listed-characteristic-and-mixed-radiological-wastes

Guidelines 10: Data quality of life cycle flows	
10.4	The precision of flows derived from the building model shall be in alignment with current practice (i.e., those typically attained from BIMs, cost reports, construction documents, energy simulation, etc.). Note: BIMs are very precise but may lack good detail for the timing of the assessment. When product quantities are calculated using takeoff software the precision is much more variable; however, there is more control over the detail taken from the building model (in this case, the building design drawings).
10.5	The bill of flows shall be sufficiently representative of the i) technology coverage, ii) time period, and iii) geographical coverage of the building, as defined by its functional equivalent, to meet the purpose of the assessment. Note: Flow quantities that are measured or derived from the building model are well representative of the building project. Selection of other flow and scenario data (e.g., from product-specific or secondary sources), however, should consider these three criteria. For example, if the product quantities of a wood roof truss are not available, industry-average quantities may be used; however, they should be selected on the basis of the technology and geographical coverage, and time period the values represent.
10.6	The consistency of a life cycle bill work may be improved by: • completeness: applying the same level of rigor in compiling flow quantities across all building elements and information modules included in assessment scope, • precision: minimizing the number of methods used to derive flow quantities (e.g., BIM vs. takeoff software, energy simulation vs. utility bills) and data sources, • representativeness: maximizing the use of project-related information (e.g., the building model, measurement) to derive flow quantities, as these sources provide information that is consistently the most representative of the building project, and • reproducibility: applying the same level of rigor in reporting how the various flow quantities were derived, the data sources used, and the resulting bill of flows.
10.7	The life cycle flow quantities derived for a wbLCA should be reproducible. The following should be included in wbLCA reporting: a) the general method(s) by which the flow quantities were derived from the building model (e.g., name and version of software/tools used, notable calculation procedures), b) the information sources used (e.g., name of BIM file, building drawing sets and/or product/utility bills used, contractor estimates, software defaults), and c) life cycle flow quantities, either the bill of flows or the bill of materials, along with the scenarios used to derive the bill of flows. wbLCA software may be cited when default scenarios are used. The latter is often a better choice as it allows others (e.g., verifiers, green building policy administrators, etc.) to check the reported results in the same software.

Guidelines 10: Data quality of life cycle flows

10.8 The accuracy of the product flows forming the bill of materials should conform to the table below and be reported accordingly.

The accuracy of bills of materials that draw on a BIM shall be the same as those attained by quantity takeoff methods. In order to account for potential missing product quantities (e.g., concrete reinforcing), the BIM shall either be further detailed or the quantities shall be calculated using quantity takeoff methods and added to the bill of materials.

The best available information shall be used when compiling a bill of materials. When meeting requirements, the timing of assessment should be prescribed by the policy. Performance declarations shall at minimum be based on construction documents.

Note: This table below presents a framework for classifying and equating the quality of bills of materials produced using a BIM and quantity takeoff software, based on the timing of the assessment. Further research will be required to refine the requirements.

Note: LOD means level of development. For an explanation of the cost estimate accuracy classifications (denoted as quantity takeoff), see Table 3.

Accuracy guidelines for product flows forming the bill of materials:

State of project and available Information	**BIM** [18]	**Quantity takeoff**		
		Canada CCA method [21]	**U.S.** ASPE method [17]	**U.S.** AACE method [34]
Preliminary: when no design information is provided; may be based primarily on building square footage or programming (i.e. functions).	LOD 100	Class D	Level 1	Class 5
Schematic design: when the building model has very little design information and the primary building systems options are being evaluated and therefore possibly subject to change.	LOD 200	Class C	Level 2	Class 4
Design development (DD): the primary building system design choices are set and the design is being further detailed. The percent completion of this phase should be given (e.g., DD phase, 60%).	LOD 300	Class B	Level 3	Class 3
Construction document (CD): the building model reflects the design during the construction phase. The percent completion of this phase should be given (e.g., CD phase, 80%).	LOD 300-400	Class A	Level 4	Class 2

Guidelines 10: Data quality of life cycle flows						
	Building Operation: the building model reflects the building design during its use. The year post completion should be given (e.g., Use phase; year 15).	LOD 300-400	Class A	Level 4	Class 2	
	Refurbishment: the building model reflects a refurbishment to the building design during its use phase. The design/construction phase of the refurbishment project should be given along with the year post-initial completion (e.g., refurbishment; DD phase, 75%; year 15).	Per the state of the project during refurbishment (e.g., design development vs. construction document).				
	End-of-life: the building model reflects the design just prior to deconstruction/demolition.	LOD 300-400	Class A	Level 4	Class 2	

5. Selection of environmental data

In order to calculate indicator results for a building (Section 6), environmental data must be selected for each flow in the bill of flows. The environmental data links the quantities of calculated flows to their resulting environmental effects. This section describes the types of environmental data used in wbLCA and corresponding data quality issues.

5.1. Sources of environmental data

There are two sources of environmental data commonly used in wbLCA, as described below.

LCA databases

These databases include life cycle inventories for the various activities a building undergoes and a life cycle impact assessment (LCIA) method. A life cycle inventory (LCI) is a list of input and output flows for a particular technosphere process (e.g., steel production). In this case, flows are emissions to air, land and water, plus resource use, such as materials, energy and water. For example, the manufacturing process of a construction product may emit carbon dioxide and methane to the atmosphere, both of which are greenhouse gases that cause climate change. A life cycle impact assessment (LCIA) method is a set of characterization factors that are applied to an LCI to arrive at environmental indicator results. These results may estimate “end-point” impacts, such as damage to human health, or “mid-point” impacts, such as global warming potential. The use of mid-point indicators for wbLCA is more common at present; consequently, such mid-point indicators are referenced and used in this document.

Environmental product declarations

Environmental product declarations (EPDs) are documents that summarize the results of a life cycle assessment of a product or service. The LCA is performed in accordance with product category rules (PCR), which are consensus-driven product-specific instructions for developing EPDs. The organizations that manage EPD programs and publish them are called program operators. Each EPD must be third-party reviewed for conformance with LCA standards and the relevant PCR prior to publication.

EPDs are available for many products; however, consistency and comparability need to be considered when using this data in a wbLCA. Factors that affect consistency and comparability include LCA method and background data used for the EPD, life cycle scope and functional equivalence. In addition, scenarios need to be considered for EPDs that do not cover the full life cycle. ISO 21930:2017 Clause 5.5 provides a detailed list of conditions for EPDs that must be met before using them for this purpose. Consistency in EPDs and their utility for wbLCA will be improved when all North American PCRs are in compliance with the same set of core rules (ISO 21930:2017), when EPDs draw on the same background data sets, and when EPDs provide uncertainty analysis.

Types of environmental data and how they are selected

Environmental data selection is the process of assigning datasets to each quantity in the bill of flows. The overall approach depends on the method used to derive flows (Methods 1, 2, 3 – see Section 4.2).

Table 6 summarizes the types of environmental data typically required for wbLCA, and the types of flows for which they are selected – note that there are two sections to the table which cover datasets for either Methods 1 and 2, or Method 3.

Table 6: Types of environmental data

Environmental data types (unit)	Description	Corresponding flow types (default unit)
Datasets for when the bill of flows has been compiled according to Method 1 and 2		
product use (declared unit)	These datasets only cover the cradle-to-gate production of products (modules A1-A3) and must be paired with other processes to complete the life cycle of products in the context of the building. This type of dataset is based on a declared unit.	*product* (m^3, tonnes, etc.)
product emissions (declared unit, as a function of time)	These datasets cover module B1 emissions from materials (e.g., off-gassing) and to materials (e.g., carbon uptake from carbonation) during the use phase. This type of dataset is based on a declared unit as a function of time to account for different building service lives.	*product* (m^3, tonnes, etc.)
transport (MJ, t*km, L, etc.)	Processes that cover the array of possible transport modes (such as truck, rail, barge, ocean, etc.) by fuel type. t*km-based data typically includes accounting of backhauls.	*transport-energy* (MJ, t*km, L, etc.)
energy use (MJ, L, kWh, etc.)	Processes that cover the types of energy used on site for construction activities or for building operation. E.g., grid electricity, diesel, heating/cooling from a district plant, etc.	*construction-energy*, *operational-energy* (MJ, L, kWh, etc.)
water use (m^3)	Water use processes, which will have different environmental outcomes depending on the type of tap water production.	*construction-water*, *operational-water* (m^3)
waste processing (kg) *waste disposal* (kg) *wastewater treatment* (m^3)	Waste processing includes processes for handling /preparing materials that are to be recycled, reused, etc., or sorting for eventual disposal. Disposal processes include landfilling and incineration. Wastewater treatment includes the wastewater treatment process and other waste processing (e.g., residues).	*waste* (kg), *construction-wastewater*, *operational-wastewater* (m^3)
recycling (kg) *reuse* (kg) *energy recovery* (kg) *exported energy* (MJ)	Processes that convert the net output flow to an environmental benefit or load beyond the system boundary. See Section 6.2 for how these datasets are calculated.	*net output flow* (kg) *exported energy* (MJ)
Datasets for when the bill of flows has been compiled according to Method 3		
A1-A3, A4, A5, B1, B2, B3, B4, B5, B6, B7, C1, C2, C3, C4, D1, D2, D3, D4 (functional unit)	Environmental data, by information module. These types of data include scenarios (i.e., cover at minimum some of the A4-A5, B and C modules) and are based on a functional unit.	*product* (m^3, tonnes, etc.)

Flows derived according to Method 1 and 2 quantify the inputs (resource use) and outputs (waste) of the various life cycle activities through the use of scenarios – see Figure 11 for how this is done. Environmental data that reflects each activity is assigned to the flows. For product flows, this is the environmental impact of products from raw material extraction through manufacturing (modules A1-A3) on the basis of a *declared unit*. A *declared unit* is a unit of product with an unidentified end-use function. For example, "m^3 concrete" and "tonnes steel" are units that specify the product type, but do not provide details on the product's functional requirements.

Environmental data for energy use and transport account for resource extraction through use/combustion, while water use datasets account for extraction up to the point of water use. Data that accounts for the environmental impact of waste outputs typically includes the various processes required for the waste to exit the system boundary; e.g., the various activities that occur during landfilling operations.

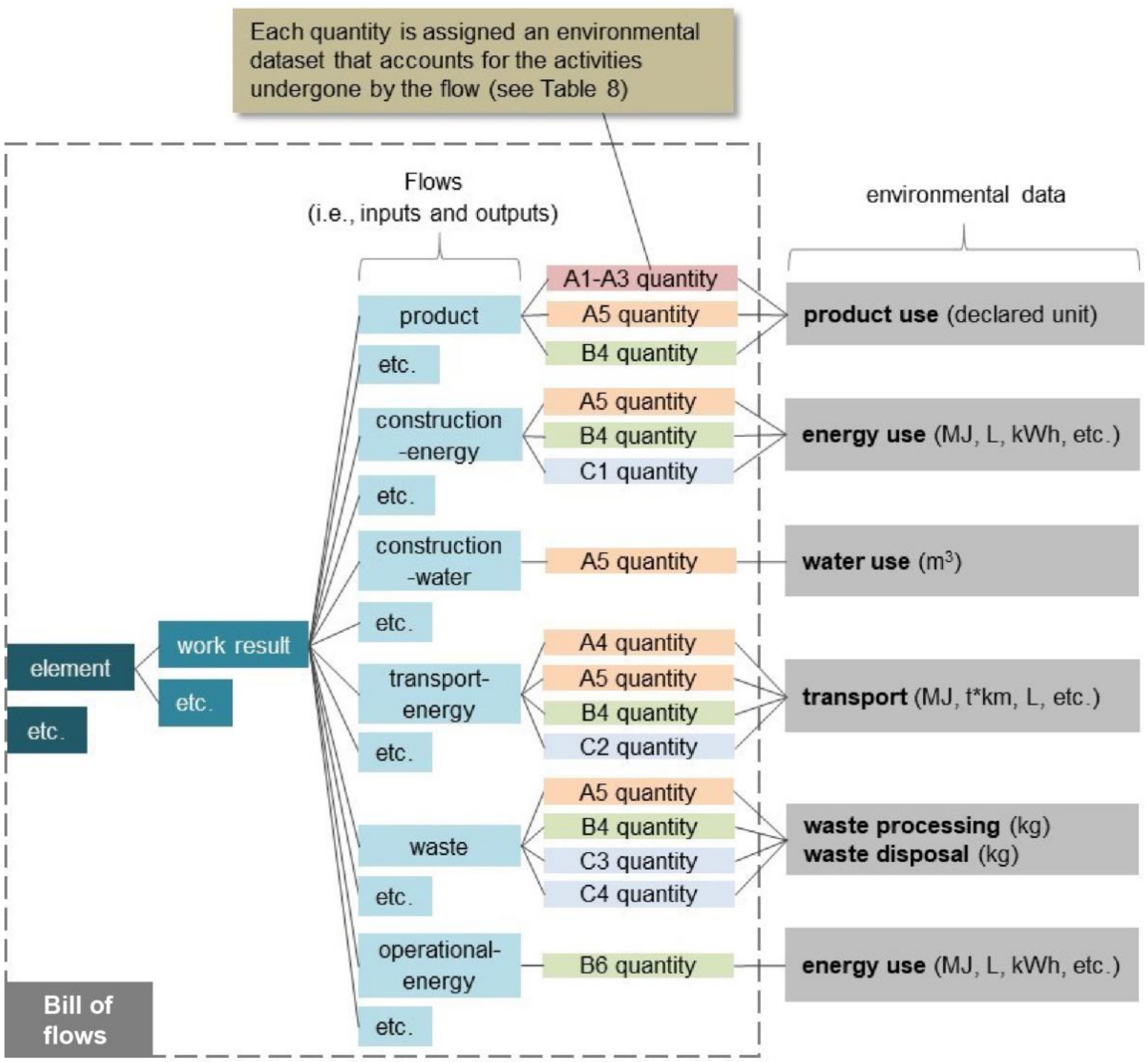

Figure 11: Selection of environmental data for a bill of flow derived from Method 1 or 2

Figure 12 shows how environmental data is selected for flow quantities that are derived according to Method 3 (See Section 4.2). This is the case where a product flow originating from the bill of materials will be evaluated with environment data that covers its life cycle, based on a *functional unit*. Per ISO 21930:2017, a functional unit is a “quantified performance of a product system for a construction product or construction service for use as a reference unit in an EPD based on LCA that includes all stages of the life cycle.” This means that data for each module already has the appropriate scenarios accounted for, so the product quantity is assigned the environmental data for each. Note that the service life use stage data (modules B1-B5) is based on might not align with the reference study period of the wbLCA and may need to be adjusted accordingly.

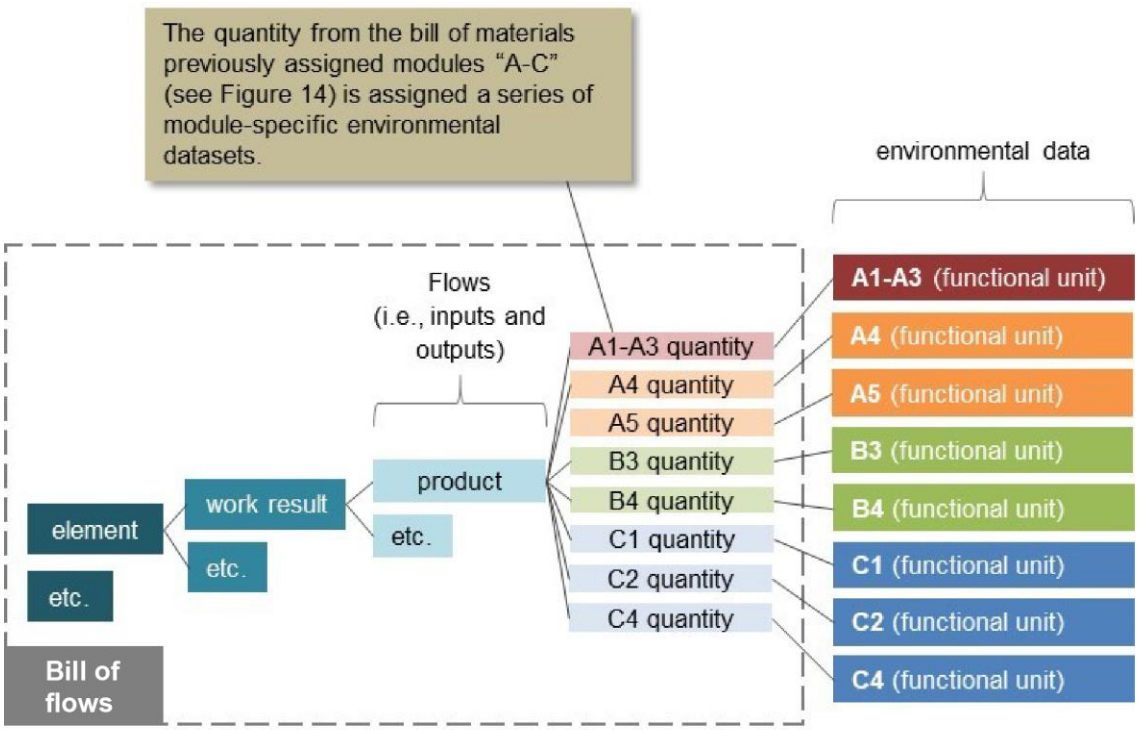

Figure 12: Selection of environmental data for a bill of flow derived from Method 3

5.2. Quality of environmental data

Environmental data has typically already been validated for completeness, reproducibility and precision, through, for example, a third-party review process, by the time it reaches a wbLCA practitioner. For the wbLCA practitioner, the remaining task is to select environmental information, based on product-level data quality information that is mutually consistent and representative of the products and services the building uses.

The most difficult metric to assess is consistency between datasets. Inconsistency across sets of environmental data can arise due to many different factors and can lead to unreliable wbLCA results. Ideally, the wbLCA tool will have addressed the harmonization of its data and therefore consistency is not an issue to the practitioner except in cases where the practitioner wishes to add environmental data from another source, such as an EPD. One sign that a particular dataset may be incompatible is if it results in a disproportionately large/small contribution to one or more building impacts – this may be the result of differences in the choice of underlying data; e.g., from proprietary or national databases other than those used in the wbLCA model.

Selecting data that is not representative of the project can lead to inaccurate results and erroneous conclusions. To help explain this, consider an assessment in which the building uses significant grid electricity during operation. The selection of appropriately representative electricity data is key to producing good indicator results as it will undoubtedly be a significant contributor to impact. If an old dataset is used, it may represent a generation mix that is very different from the present state. Similarly, a dataset that does not cover the appropriate technologies used (i.e., generation mix) will not yield an accurate estimate either. Finally, if the dataset represents another geographic locale with a different generation mix, the calculated wbLCA results may be erroneous, possibly by as much as an order of magnitude.

Guidelines 11: Selecting environmental data	
11.1	Practitioners shall by default rely on data built into wbLCA tools provided that it conforms with these guidelines.
11.2	The default industry-average data for Canadian buildings shall come from the Canadian Construction LCI (CCLCI) project. Note: The NRC's CCLCI project will provide individuals with accounting of the energy and material flows into and out of the environment that are associated with producing construction materials, components or assemblies in Canada.
11.3	Environmental data selected for a wbLCA shall meet the requirements of ISO 14044:2006 and should also meet the requirements of ISO 21930:2017.
11.4	Environmental data should be current and geographically representative for the building location and the products used.
11.5	EPDs used as environmental data for wbLCA should not be expired and shall: a) when applicable, meet the comparability requirements of ISO 21930:2017 Clause 5.5, b) be applicable to the project location, c) use the same LCIA methodology as the wbLCA study, d) report all indicators and information modules required for the purpose of the wbLCA study, and e) align with or can be modified to align with the reference study period of the wbLCA study.
11.6	Combining environmental data that draw on different background LCI databases should be avoided.

Guidelines 11: Selecting environmental data	
11.7	Environmental datasets shall not reflect the purchase of carbon offsets, renewable energy certificates (RECs) and/or bundled green power products.
11.8	Use stage environmental datasets based on a functional unit (labelled B1, B2, B3, B4, B5, B6, B7 in Table 8) shall be adjusted, when relevant, for the required service life of the building and the reference study period.
11.9	The selection of environmental datasets based on a functional unit (labelled A1-A3, A4, A5, etc. in Table 6) shall take into consideration the activities covered (as delineated in Appendix C) and the defined system boundary of the assessment.

6. Calculation of the environmental indicators

This section addresses the calculation of wbLCA results (environmental indicators). It describes environmental indicators to be reported in wbLCA and the calculation method. In addition, this section provides guidance for two factors not addressed in EN 15978:2011: biogenic carbon and concrete carbonation. This section also provides guidance for results interpretation, which is not addressed in EN 15978:2011.

6.1. Environmental indicators

Environmental indicators are used to describe environmental impacts (e.g., a global warming potential of 1,000 tonnes CO_2 eq.) and resource use (e.g. 1,000 MJ of non-renewable primary energy). Calculation of an environmental indicator result for the full building life cycle is done according to Equation 4. This equation sums the environmental indicator results of each flow, for each work result, element and information module, to arrive at a final life cycle result for the building. Any other set of indicator results (e.g., by element, work result, information module, flow) can be calculated as a subset of this equation. See Appendix C for all calculations required by the EN 15978 system boundary.

Equation 4: Calculation of environmental indicators

$$\mathbf{EI}_{m} = \sum_{l=1}^{n} \sum_{k=1}^{n} \sum_{j=1}^{n} \sum_{i=1}^{n} (\mathbf{ED}_{i,l,m} \times \mathbf{FQ}_{i,j,k,l})$$

where,

EI_m	is the environmental indicator result for indicator m
i	is a flow of the bill of flows
j	is the work result of flow i
k	is the element of work result j and flow i
l	is the information module flow i pertains to
m	is the environmental indicator type
$ED_{i,l,m}$	is the environmental indicator value corresponding to flow i, for information module l and indicator m
$FQ_{i,j,k,l}$	is the quantity for flow i, in work result j, and element k, that pertains to information module l

Note: Equation 4 is adapted from EN 15978:2011 Clause 11.2

The selection of environmental indicators to be calculated is dictated in EN 15978:2011 Clause 11.1 – a total of 22 indicators are identified. However, this is superseded by ISO 21930:2017 Clause 9.5, which expands the list for a total of 31 indicators. See Appendix D for both lists.

A life cycle impact assessment (LCIA) method provides environmental impact characterization factors for its set of impact indicators. In North America, the LCIA method TRACI v2.1 [24] is most commonly used and thus is set as the North American default in ISO 21930:2017 Clause 7.3. TRACI has five core indicators:

- global warming potential[15] (kg CO_2 eq.),
- acidification potential (kg SO_2 eq.),
- eutrophication potential (kg N eq.),
- photochemical smog potential (kg O_3 eq.), and
- ozone depletion potential (kg CFC-11 eq.)

There are four energy use indicators (two renewable, two non-renewable) required by EN 15978 and ISO 21930. These are based on *net calorific values* (i.e., “lower heating values”), which are the quantities of energy used when the water vapor produced during combustion of fuels remains a gas. Note that some software may still report *gross calorific values* (i.e., “higher heating values”), which also accounts for the energy content for water vapor condensing.

There are other indicators that are calculated by summing LCIs. These include:

- water and other resource use indicators,
- waste indicators. These report the LCI flows of different types of waste (in kg) to disposal; output flow indicators similarly track the quantities of waste that are processed for secondary use in another life cycle (e.g., materials for recycling), and
- removals and emissions associated with biogenic carbon, and calcination/carbonation.

While EN 15978 and ISO 21930 specify a long list of indicators to be calculated, this may not always be possible or appropriate. One factor is data availability; the wbLCA software used may not support all indicators, or the underlying LCI or EPD data may not include all indicators. Another factor is the purpose of the assessment; some indicators may not be needed if they don’t serve the purpose of the assessment.

[15] Global warming potential includes both fossil and biogenic emissions and removals. Emissions and removals resulting from land use change are not widely reported in product LCA, but when data becomes more widely available should also be incorporated into the GWP result.

Guidelines 12: Selecting LCIA method and impact indicators	
12.1	wbLCAs shall at minimum report the TRACI indicators' global warming potential, acidification potential, eutrophication potential, and smog potential, plus non-renewable primary energy, excluding resources used as raw material. A rationale should be provided in cases where an LCIA method other than TRACI v2.1 is used. Note: Ozone depletion potential (kg CFC-11 eq.) is another common indicator used in wbLCA; however, the LCI flows that cause this impact are currently of poor data quality.
12.2	When included in reporting, inventory-based indicators shall be calculated in accordance with ISO 21930:17 clause 7.2 and may also be guided by ACLCA Guidance to Calculating Non-LCIA Inventory Metrics in Accordance with ISO 21930:2017 [25].
12.3	wbLCA indicator results for primary energy consumption may be either gross or net calorific values, and this distinction shall be reported. Gross and net calorific results shall not be added. Adjustments may be made to convert gross calorific results to net calorific results (and vice versa); the method used should be documented.

6.2. Module D

Whole-building LCA per EN 15978 is an attributional analysis[16] wherein the system boundary is terminated when waste streams reach the system boundary between product systems. As described in EN 15978 Clause 7.4.6 D and further characterized in ISO 21930 Clause 7.1.7.6, module D accounts for potential environmental benefits and loads that occur after this point (e.g., the benefit of a reused product in the next life cycle). This information can be used to understand implications beyond the system boundary, which may, for example, influence upfront design decisions such as waste management plans and deconstructability.

In accordance with ISO 21930:2017 Clause 5.5, the module D results of an EPD must not be aggregated with information modules A to C as they lie outside the system boundary of the building; the same rule applies to wbLCA. Module D effects covered by EN 15978:2011 include:

a) recycling (D1),

b) reuse (D2),

c) energy recovery (D3), and

d) exported energy (D4).

Environmental benefits and burdens beyond the system boundary are calculated according to Equation 5.

[16] Attributional LCA estimates the share of environmental impact a process is responsible for. In contrast, consequential LCA aims to estimate the change in environmental impact due to changes in production, use, etc.

Equation 5: Calculating module D life cycle inventory of a secondary product or fuel

$$LCI_D = NF \times CF \times (lci_2 - lci_1)$$

where,

LCI_D	is the module D substitution effects LCI of the secondary product/fuel
NF	is the net output flow of the secondary product/fuel
CF	is a justified correction factor to reflect the difference in functional equivalence where the processed net output flow does not reach the functional equivalence of the substituting process
lci_2	is the LCI of any further processing of the secondary material occurring beyond the system boundary that is required to reach the point of substituted functional equivalence
lci_1	is LCI for producing the product/energy that is substituted, up to the point of functional equivalence

Note: this equation is an interpretation of the intent expressed in EN 15978:2011 and ISO 21930:2017.

In Equation 5, the net output flow (NF) is the difference between the recovered secondary product or fuel leaving the product system and the secondary product or fuel that was used by the system, for all relevant information modules included in the life cycle of the object of assessment. It represents the net amount of secondary material or fuel added to, or removed from, the technosphere.

In Equation 5, CF ($lci_2 - lci_1$) is the net environmental value of producing materials/energy via secondary vs. primary production, per unit net output flow; see Table 7 for common examples.

The application of Equation 5 can be illustrated with an example. Consider a steel beam that has 90% recycled content, 98% of which is recycled at end-of-life. In this case, the net output flow is 0.08 kg/kg steel (0.98 – 0.90 = 0.08). This results in an environmental *benefit* outside the system boundary, because there is now more secondary steel available in the technosphere, and secondary steel production causes less impact than primary production (i.e., CF ($lci_2 - lci_1$) is an LCI that produces negative environmental indicator results). In contrast, the net output flow of a steel beam with 50% recycled content that is completely landfilled is –0.5 kg/kg steel (0.0 – 0.5 = –0.5). Since secondary steel is removed from the technosphere, module D reports an environmental *load* outside the system boundary. In each case, the end-of-life impacts of the beam up to the demarcation between product systems (e.g., from demolition, transport, waste processing, landfilling, etc.) are allocated to modules C1 to C4.

Table 7: Typical module D substitution effects

Product	Description
D1 Recycling[a]	
Steel and aluminum	Secondary metals substitute for primary metal production. CF ($lci_2 – lci_1$) is the difference between secondary and primary metals production (i.e., the "scrap value").
Concrete and masonry	Concrete/masonry is crushed and used as aggregate. CF ($lci_2 – lci_1$) is the difference between the effects of crushing and transporting concrete/masonry, and module A1-A4 effects of primary aggregate production (i.e., quarrying, crushing, transporting). Note that this process may affect the rate of carbonation for concrete products.
Any product	Post-consumer waste substitutes primary materials in the production of a product. CF ($lci_2 – lci_1$) is the difference between the module A1-A4 effects of producing the product with recycled content and primary production.
D2 Reuse	
Any product	Reused materials substitute for products made from primary production. CF ($lci_2 – lci_1$) is the difference between the module A1-A4 effects of the reused product and primary production.
D3 Energy recovery	
Any product (bio- or, fossil-fuel-derived)	Combustion of waste (e.g., wood waste) produces heat and/or electricity. CF ($lci_2 – lci_1$) is the difference between the cradle-to-combustion effects of the waste and conventional sources, on a per MJ net calorific value basis.
D4 Exported energy	
Any energy type (heat or electricity)	An excess of operational energy is produced at the building site and provided to market. Since the burden of the energy produced on site is accounted for in module B6, it is considered burden-free leaving the site and CF ($lci_2 – lci_1$) is simply the cradle-to-combustion effects of equivalent conventional energy production.

[a] Note that wood products which are recycled by being chipped and used as landscaping material (e.g., mulch) aerobically decompose over time and releases biogenic CO_2.

EN 15978:2011 Clause 7.4.6 and ISO 21930:2017 Clause 7.1.7.6 require that the scenarios and assumptions[17] used to calculate module D reflect average existing technology and current practice. This provision acknowledges the attributional nature of the standard's calculation method and appropriately constrains results from unknowable claims about the future.

Guidelines 13: Module D	
13.1	The method for calculating and reporting any optional supplementary information regarding potential loads or benefits beyond the system boundary under module D shall comply with ISO 21930:2017 Clauses 7.1.7.6 and 9.4.7.

[17] Examples include scenarios and assumptions on waste outcomes (i.e., % of waste to recycling, reuse, landfilling, incineration), energy recovery rates, waste processing technology, and conventional energy source mix alternatives.

6.3. Carbon analyses not covered by EN 15978

While ISO 21930:2017 incorporates biogenic carbon accounting and concrete carbonation into EPD requirements, the treatment of these carbon flows at the building level are not covered by EN 15978:2011. This section explains biogenic carbon accounting and concrete carbonation per ISO 21930:2017 and how they can be incorporated into wbLCA practice.

6.3.1. Biogenic carbon accounting

Bio-based materials are those that are manufactured from renewable resources such as trees and other living organisms. The physical carbon in such biomaterials is referred to as biogenic carbon and is subject to specific accounting rules in ISO 21930:2017 Clauses 7.2.7 and 7.2.12. In accordance with ISO 21930, biogenic carbon removals and emissions must be accounted for in the life cycle inventory and global warming potential of EPDs for products that contain biomass. Biogenic carbon should similarly be accounted for and reported in wbLCAs. For a standardized calculation methodology for computing the amount of biogenic carbon within a bio-based product, see EN 16449: 2014 [32].

Per ISO 21930:2017 Clause 7.2, the biogenic carbon flows in the product system shall be accounted and reported in the modules in which the flows take place. See Figure 13 for a representation of biogenic carbon flows in the relevant modules. ISO 21930:2017 Clause 7.1.5 requires the removal of carbon dioxide from the atmosphere be accounted for within module A1, and the same convention is assumed here for wbLCA.

Biomass sequesters carbon from atmospheric carbon dioxide as it grows and, upon decomposition, releases carbon back to the atmosphere as either carbon dioxide (aerobic decomposition) or methane (anaerobic decomposition). See the UL Wood PCR Part B [33] for additional guidance on calculating the conversions and emissions of biogenic carbon from landfills.

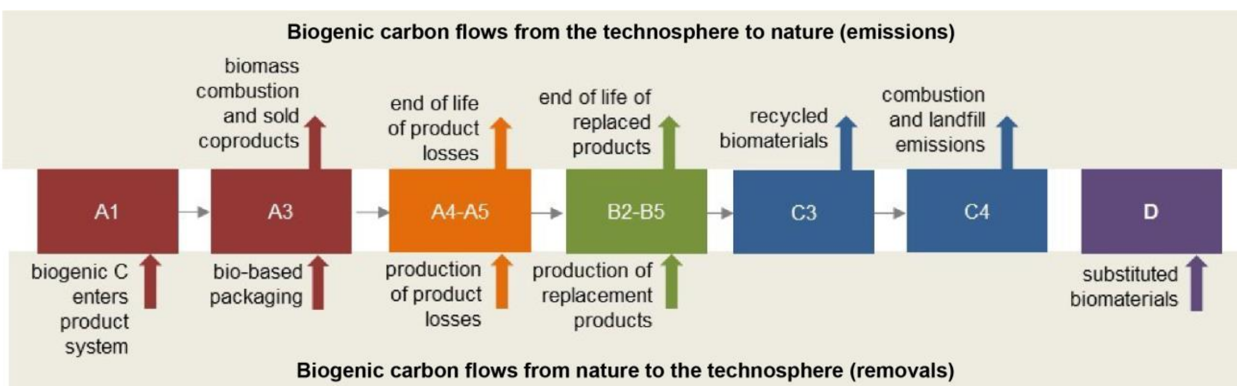

Figure 13: Examples of biogenic carbon flows throughout the life cycle

Removal of carbon dioxide from the atmosphere is considered a negative emission in the calculation of the global warming potential (characterization factor of -1 kg CO_2eq/kg CO_2) if the biomaterial can be shown to originate from sustainably managed forests. Per ISO 21930:2017 Clause 7.2.11, sustainable forest management can be indicated through industry certification programs and/or “other evidences”, such as national reporting under the United Nations Framework Convention on Climate Change (UNFCCC) [27] if this shows stable or increasing forest carbon stocks. Table 6-1 of the American and Canadian UNFCCC annual reports [28, 29] provides annual net GHG flux estimates for different land use categories. This reporting indicates non-decreasing forest carbon stocks in both countries and thus the default assumption is that the source forests meet the conditions for characterization of removals with a factor of –1 kg CO_2e/kg CO_2.

The carbon removal attributable to the biomaterial is calculated based on the mass of material that flows into the building system boundary – as both virgin material and that which is reclaimed or recycled from a previous building life cycle.

Some biogenic carbon in the material entering the product manufacturing module (A3) leaves the system as combustion emissions, as sold coproducts and as waste. The sold coproducts are treated identically to material that is combusted[18], with all material leaving the system boundary in this module accounted as a direct emission and characterized with a factor of +1 kg CO_2e/kg CO_2. Wood waste that enters the landfill will have long-term decomposition, landfill gas capture and subsequent landfill gas combustion emissions to consider in the biogenic carbon accounting.

The portion of the bio-based product that is lost as waste (i.e., not part of the installed product) during construction (module A5) is accounted the same as production waste. The construction waste that is burned or enters another product system is accounted as a direct emission and characterized with a factor of +1 kg CO_2e/kg CO_2. The long-term emissions from landfilled construction waste are considered in module A5. All bio-based material inputs in module A5 that originate from sustainably managed forests are characterized by a factor of -1 kg CO_2e/kg CO_2. All biogenic carbon emissions and biomaterials leaving the product system are characterized by a factor of +1 kg CO_2e/kg CO_2.

As with all materials, the B2 to B5 modules consider the amount of product required in addition to the initial construction. The biogenic carbon accounting for these materials follows the same procedure as the previous modules. Namely, the A1 to A3 biogenic carbon flows for the initially installed products are included in the B2 to B5 modules when these products are used in the building’s maintenance, repair, replacement, and refurbishment. The bio-based materials that are removed during the use of the building and subsequent emissions from their treatment (i.e., combustion, landfilling or recovery) are reported in the relevant B2 to B5 module.

At the end-of-life of a building, demolition debris may be separated and a portion recovered for use as a fuel or secondary material in a new product system. In the case of waste diversion, all bio-based materials that leave the product system for combustion or recycling/reuse are accounted as an emission in module C3 and characterized with a factor of +1 kg CO_2e/kg CO_2.

[18] Emissions other than CO_2 associated with biomass combustion (e.g., methane or nitrogen oxides) are characterized by their specific radiative forcing factors in the calculation of the GWP.

The biogenic carbon accounting of wood waste that enters the landfill will consider the long-term decomposition, landfill gas capture and subsequent landfill gas combustion emissions in the biogenic carbon accounting.

The biogenic carbon dynamics in the landfill may be estimated based on modelling published by the U.S. EPA [26]. The EPA created the Waste Reduction Model (WARM) to track greenhouse gas emissions reductions, energy savings and economic impacts from several different waste management practices. WARM calculates and totals these impacts from baseline and alternative waste management practices: source reduction, recycling, anaerobic digestion, combustion, composting and landfilling.

Guidelines 14: Biogenic carbon	
14.1	Biogenic carbon should be included in wbLCAs.
14.2	When included in assessments, biogenic carbon flows shall be accounted for and reported in the modules in which the flows take place.
14.3	Biogenic carbon accounting shall be in accordance with ISO 21930:2017 and may also be guided by ACLCA Guidance to Calculating Non-LCIA Inventory Metrics in Accordance with ISO 21930:2017 [25].
14.4	Scenarios used to calculate biogenic carbon removals and emissions shall be representative of contemporary technology or practice. Note: Examples of scenarios include waste outcomes (i.e., % of waste to recycling, reuse, landfilling, incineration, energy recovery rates, waste processing technology, etc.), biomass decomposition rates, etc. Other scenarios may be considered for assessment purposes not covered in this document; e.g., end-of-life planning, research**.**

6.3.2. Concrete carbonation

Carbonation is a naturally occurring reaction in concrete products when atmospheric CO_2 (in the presence of water) reacts with the cement. The product of this reaction is calcite (limestone), and carbon is sequestered in the process. Carbonation increases the strength of concrete; however, it also creates an acidic environment, which can corrode steel reinforcing bars. This is one reason why rebar is specified with concrete cover requirements.

Carbonation is essentially the opposite reaction to calcination, the process by which CO_2 is emitted from ground limestone during cement clinker production. Calcination and carbonation reactions occur during the life cycle of a building, as concrete is produced and then left to carbonate during storage, use or as waste under different exposure conditions. See Figure 14 for an illustration of these flows over the life cycle of concrete in a building.

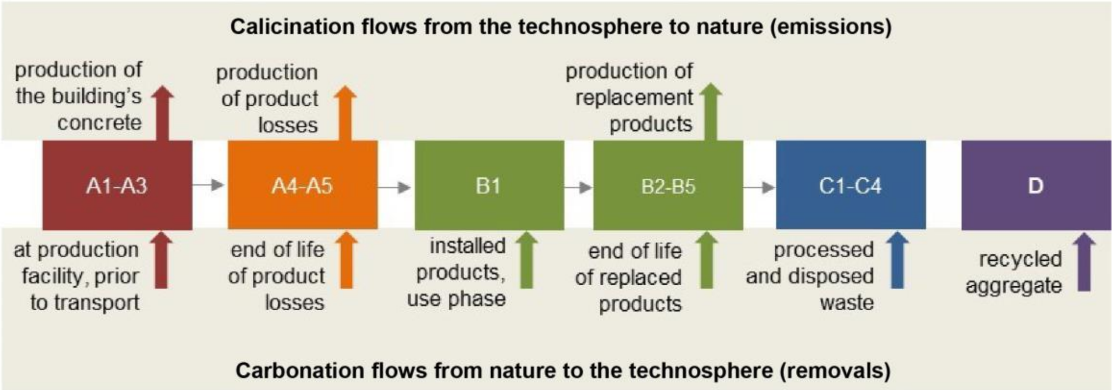

Figure 14: Examples of calcination/carbonation flows throughout the life cycle

In accordance with ISO 21930:2017 Clause 7.2.8, carbon uptake due to carbonation must be accounted for in the life cycle inventory and global warming potential of concrete product EPDs[19]. The ISO 21930:2017 requirements on carbonation can be applied to wbLCA.

Calcination occurs in the production modules for concrete products. Carbonation is a more complicated reaction pathway that happens over a much greater time period.

ISO 21930:2017 Clause 7.2.8 states that "environmental benefits attributed to carbonation in a product shall not be allocated to co-products or secondary materials." This implies that no carbonation uptake should be applied to module A1; for example, for recycled concrete used as aggregate in new concrete products.

Carbonation can first occur in precast products such as concrete blocks during storage at the manufacturing facility (A3). The transport and construction activities of modules A4 and A5 produce concrete waste; carbonation occurs during processing and/or disposal of these waste streams. During the use phase, installed concrete products carbonate over time (B1). If concrete is replaced during building occupancy, the concrete waste will carbonate during processing and disposal (B2-B5). Finally, during the building's end-of-life phase (C1-C4), the concrete waste is usually either sent to landfill, or crushed as aggregate. Carbonation occurring in the landfilled portion of the waste is allocated to the building of study. Carbonation occurring in the portion of waste that is crushed and used as aggregate is no longer within the building system boundary. Any of the additional carbonation benefit that takes place in the aggregate is calculated in the context of module D, as it occurs outside the system boundary.

This document recommends the calculation methodology in the European PCR for concrete products, EN 16757:2017, Annex BB [19]; however, other recognized alternative methods may be used. For more background information on carbonation and how it is calculated, refer to EN 16757, along with the complementary European technical report EN/TR 17310:2019 [20].

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[19] Note that requirements for carbonation are not covered in the North American PCR for ready-mixed concrete [31] and other concrete products (e.g., concrete block) as they presently only cover information modules A1 to A3, when little-to-no carbonation occurs.

The three primary equations required to calculate the carbon uptake of a concrete product are provided below. Equation 6 is used first to calculate the theoretical maximum amount of carbon uptake for the type of cement used. This amount is proportional to the content of calcium oxide (CaO) found in the clinker, which is typically in the range of 0.60 to 0.65 for Portland cement.

Equation 6: Calculating maximum theoretical CO_2 uptake of a cement product

$$U_{tcc} = w \times (m_{CO2} / m_{CaO})$$

where,

U_{tcc}	is the maximum theoretical uptake, in kg CO_2/kg cement
w	is the proportion of reactive CaO, in kg CaO/kg cement
m_{CO2}	is the molar weight CO_2 (44 g/mol)
m_{CaO}	is the molar weight CaO (56 g/mol)

Equation 7: Calculating depth of carbonation from the surface of a concrete product, as a function of time

$$d = k \times s \times t^{0.5}$$

where,

d	is the depth of carbonation (mm)
k	is the k-factor (mm/year$^{0.5}$) – see Appendix E for values
s	is the s-factor (unitless) – see Appendix E for values
t	is the time (year)

Equation 8: Calculating CO_2 uptake of a volume of concrete, as a function of time

$$CO_2 = d / 1000 \times A \times U_{tcc} \times C \times D_c$$

where,

CO_2	is the uptake of CO_2 by the concrete element, in kg CO_2
d	is the depth of carbonation, in mm – see Equation 7.
A	is the surface area of the concrete product that is undergoing carbonation, in m^2
U_{tcc}	is the maximum theoretical uptake, in kg CO_2/kg cement – Equation 6
C	is the cement content of the concrete, in kg/m^3
D_c	is the degree of carbonation, in % – see Appendix E for values

Note: Equations 6, 7 and 8 are adapted from EN 16757:2017 Annex BB.

The carbonation reactions begin at the surface of the concrete and move inward as the available reactants are converted to CaO_3; see Figure 15 for an illustration of this. As seen in Equation 7, the depth of carbonation is directly proportional to the square root of the time (in years); therefore, the rate of carbonation decreases over time. This reflects the fact that as CaO_3 forms it restricts further diffusion of CO_2 deeper into the concrete.

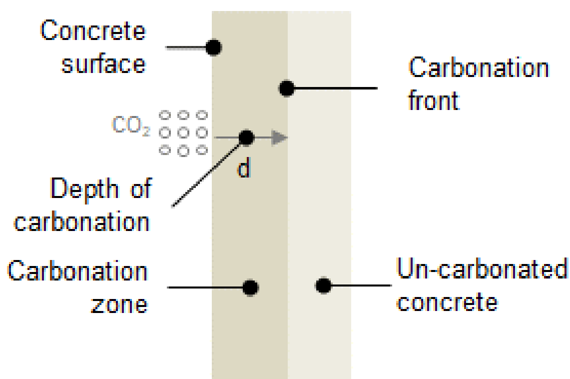

Figure 15: Carbonation at a concrete surface

The *k-factor* (mm/year$^{0.5}$) is a coefficient that describes the rate of carbonation which is dependent on two parameters:

- *Concrete strength*. Higher strength concretes generally have a higher cement content in the concrete mix design. This leads to smaller concrete pores upon curing and a slower carbonation rate.
- *Exposure condition*. The carbonation reactions require the presence of water in the concrete pores. However, too much water can impede the reaction rate, because more CO_2 will move through the concrete in solution rather than as a gas, which is slower. The exposure of concrete affects the relative humidity and the amount of water that may be in the pores; e.g., due to rain or submergence in water. Coatings on the concrete that impede movement of water and CO_2 slow the reaction rate.

Another factor affecting the rate of carbonation is the partial pressure of CO_2 in the atmosphere; higher concentrations of CO_2 lead to faster rates of carbonation. Note that the k-factors given in Appendix E account for the current partial pressure of CO_2 in the atmosphere but do not speculate on how it may change over time.

The *s-factor* is a unitless coefficient that adjusts the rate of carbonation based on the quantities of other materials that supplement Portland cement, such as fly ash, silica fume and ground granulated blast furnace slag (GGBFS or slag cement).

See Figures 16 and 17 for examples of concrete elements undergoing carbonation. Carbonation of the column in Figure 16 is occurring at each of the four faces and moving inward. The exposure condition for each face is the same, therefore the rate of uptake is the same. Figure 16 could equally be representative of, for example, beams, footings, grade beams, piers, etc. when subjected to a single type of exposure. In contrast, the wall of Figure 17 has different exposure classes on each face, and therefore the rates of carbonation moving inward into the wall are different. Figure 17 represents the general condition for plate-like concrete members, such as slabs on grade, suspended slabs, exterior/interior walls, etc.

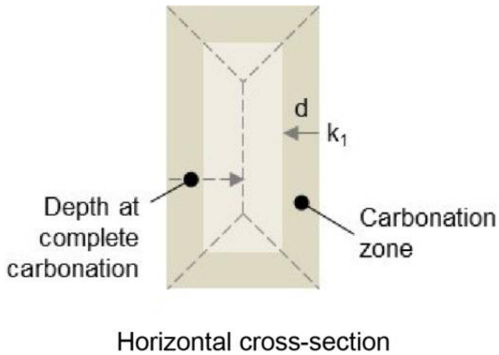

Figure 16: Carbonation of a concrete column

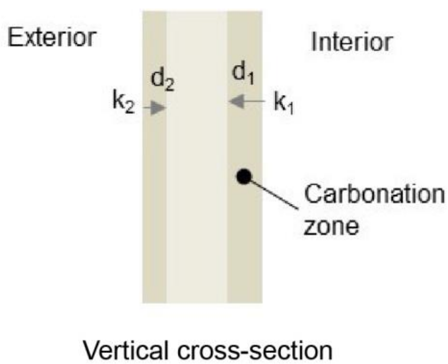

Figure 17: Carbonation of a basement wall

The total CO_2 uptake that has occurred in a concrete product over a certain period of time (years) is calculated with Equation 8. This first requires a calculation of the volume of concrete (Vc) that has carbonated. This is determined from the depth of carbonation for the volume in question, and the geometry (e.g., the area of a slab) of the concrete member being evaluated. Equation 8 contains a factor called the *degree of carbonation* (Dc), which accounts for the fact that not all available CaO will react as the carbonation front moves through the concrete. Values for Dc are similarly affected by exposure conditions, and range between 0.4 and 0.85, meaning only between 40% and 85% of the concrete volume fully carbonates. The rate of carbonation is highest in indoor environments due to quicker diffusivity of CO_2 in the dryer environment; however, the total uptake within the carbonated zone is lower due to less water available in the pores.

While the geometric properties and exposure conditions of installed concrete products are determined by the building's design, the same can't be said for concrete that becomes waste. There are many possible outcomes for concrete waste that affect the uptake of carbon, including:

- the waste outcome scenario (i.e., is the concrete landfilled or recycled?),
- the rubble or particle size, which greatly affects the available surface area for the reaction to occur,
- the state in which the rubble or aggregate is stored or disposed (e.g., is it crushed and sieved?), and
- the exposure (k-factor) and degree of carbonation (Dc) of the stockpile or disposed waste.

Guidelines 15: Concrete carbonation	
15.1	Carbonation should be included in wbLCAs.
15.2	Per ISO 21930:2017, the method used for including carbonation in wbLCA results shall be based on recognized methods and referenced in the wbLCA report. The method per EN 16757 described in this document may be used.
15.3	Scenarios used to calculate carbon uptake from carbonation shall be representative of contemporary technology or practice. Note: Examples of scenarios include waste outcomes (i.e., % of waste to recycling, reuse, landfilling, incineration, energy recovery rates, waste processing technology, etc.). Other scenarios may be considered for assessment purposes not covered in this document; e.g., end-of-life planning and research.
15.4	ISO 21930:2017 requires that carbonation results be "interpreted with respect to uncertainty of calculations." In the absence of a recognized standard approach for assessing this uncertainty, the wbLCA report may include a qualitative statement about uncertainty.
15.5	Module A3: This module may be neglected unless included in a dataset produced by the concrete product supplier.
15.6	Modules A4, A5: The carbonation of any amounts of concrete that become waste due to these activities should be accounted for, similar to modules C3-C4.
15.7	Module B1: The carbon uptake of each installed concrete element should be calculated for the required service life of the building and adjusted for the reference study period. If products are replaced (B2-B4) or added to the building during refurbishment (B5), the carbonation of these elements while installed should be allocated to this module.
15.8	Modules B2-B5: If concrete is replaced during occupancy to maintain the functions of the building (B2-B4), or due to a refurbishment project (B5), carbonation of the outbound waste should be accounted for, similar to modules C3-C4.
15.9	Modules C1-C3: These modules may be neglected, and any potential carbonation that occurs may be allocated to module C4 and/or D.

Guidelines 15: Concrete carbonation	
15.10	Module C4: Per EN 15978 Clause 10.3, 100 years of disposal effects (in this case, carbonation reactions) shall be accounted for. A very conservative approach is to assume that the concrete isn't broken up during demolition, and this module is simply allocated another 100 years of uptake with an "in ground, under the ground water level" exposure (k = 0.2, Dc = 0.85, see Table 13). Other landfill rubble/particle size and exposure assumptions may be made, provided the rationale and method are documented.
15.11	Module D: Scenarios used to calculate the carbonation of crushed concrete should account for the particle size distribution and exposure of the resulting aggregate. The rationale and method should be documented.

6.4. Results interpretation

The interpretation step of wbLCA is important. The goal in this step is to provide clarity on results, validate results and troubleshoot for errors in the model. EN 15978:2011 states that interpretation is outside of its scope, hence guidance is provided here[20].

6.4.1. Contribution analysis

Contribution analysis is the process of grouping indicator results together in different ways to better understand what is driving them. Results may be grouped by:

a) *Information module***.** Reporting indicator results by information module is already required by EN 15978, but this also highlights the time- and activity-related nature of results.

b) *Year***.** This is another way of viewing the time-related nature of results.

c) *Resource use***.** This identifies the relative impacts of the three major resource uses for buildings: material use (modules A, B1-B5, C), operational energy use (module B6) and operational water use (module B7).

d) *Element* (OmniClass Table 21). This helps identify which part of the building (for materials) or which operational energy or water end-uses are driving impact. See Figure 18 for an example.

e) *Work result* (OmniClass Table 22). This helps identify which types of building products and energy and water carriers are driving impact.

f) *Flow***.** Grouping results by flow is the most detailed contribution analysis available as this breaks results down by specific product, energy, water, and waste flows; this helps troubleshooting for issues with model datasets.

[20] For further guidance on life cycle interpretation, refer to ISO 14044:2006 Clause 4.5.

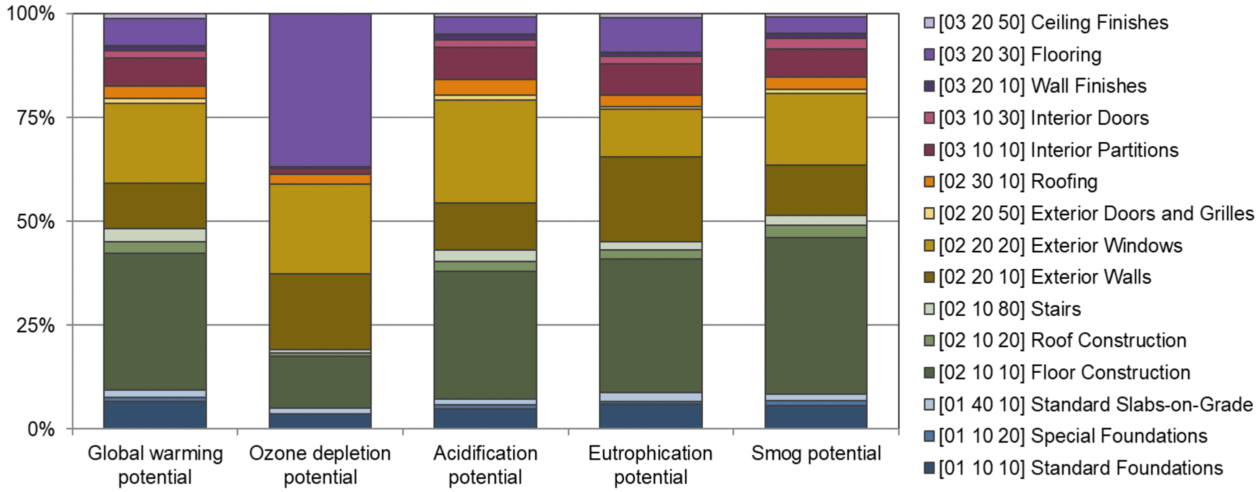

Figure 18: Example wbLCA contribution analysis, by element

6.4.2. Sensitivity analysis

Sensitivity analysis is the process of changing a parameter in a wbLCA model and recalculating indicator results to test its relative effect on the building. This may be done as part of informing building design, or as part of the process of validating wbLCA results.

EN 15978:2011 Clause 10.3, requires that "the significance of the influence of the data chosen for the building assessment shall be determined (e.g., through a sensitivity analysis) and reported."

Recommended parameters to consider for sensitivity analysis:

a) *Scenarios*. Building performance can be highly sensitive to changes in scenarios. For some flow quantities with lower data quality, analysis may be performed to test the degree to which a scenario's accuracy affects whole-building results. Other scenarios used in wbLCA are highly uncertain, particularly those that occur later in the building life[21]. Analysis can similarly be performed to explore how sensitive results are to these assumptions.

b) *A flow type*. Functionally equivalent product flows or sets of flows can be swapped to investigate their impact on results; e.g., the cladding design is changed, a natural gas furnace is substituted for a propane furnace, etc.

c) *A flow quantity*. For large contributors to product, energy or water use, even small inaccuracies in quantities can lead to large changes in indicator results. Analysis can be performed to investigate the sensitivity of potential inaccuracies by, for example, increasing a flow quantity by 10% to see the associated increase in building impact (e.g., 5%? 1%?).

[21] For example, wbLCA results are highly sensitive to end-of-life scenarios for construction waste, as the fate of the waste stream for some materials can have a large impact on their life cycle carbon balance.

d) *Environmental datasets*. The choice of environmental data can have a significant impact on building performance (e.g., the choice of grid electricity).

Guidelines 16: Contribution and sensitivity analysis	
16.1	Sensitivity analyses per EN 15978 that are appropriate for the wbLCA model and purpose of the assessment shall be performed. The data quality of life cycle flows and environmental data, the degree to which the wbLCA software's data has been validated, and significant contributors to impact should be considered when selecting analysis options.
16.2	Results of wbLCAs reporting biogenic carbon and concrete carbonation results should specify the contribution of these effects.

6.4.3. Comparing two or more buildings

Ensuring comparability of wbLCA results is important in developing and using benchmarks as well as any other circumstance where a practitioner wishes to compare results to another study. Because whole-building LCA studies involve so many variables, comparing the results of one or more buildings requires a high level of attention to alignment of study parameters.

While many of these parameters require a simple check of, for example, scope alignment, one aspect that often needs a more subjective evaluation is the degree of comparability between the functional equivalents of the buildings being compared. In some cases, this may not be an issue; e.g., when comparing the building of study to a baseline that the assessor has produced in tandem. Incompatibilities between functional equivalents may include:

- differences in one or more functional equivalent parameters; e.g., when two building types are not plausibly comparable. In many cases, smaller differences in functional equivalents may be acceptable if the assessor reasons that this does not significantly affect the ability to make conclusions and meet the purpose of the assessment,
- the scope of what is included in the functional equivalent; standardizing EN 15978 requirements across the practice reduces these types of incompatibilities, and
- the way the functional equivalents are defined; e.g., different methods of establishing the building's number of occupants. Standardizing building type via OmniClass reduces one type of such potential incompatibility.

In summary, an important requirement when evaluating the comparability of buildings is determining whether they are functionally equivalent, and this decision will be in part made using the assessor's judgement, based on the purpose of the assessment.

Guidelines 17: Comparing two or more buildings	
17.1	The buildings shall have compatible *functional equivalents*, otherwise a rationale should be provided; e.g., to meet the intended use of the assessment. Per Section 2.1: *Building type*: buildings shall have the same OmniClass Tables 11 and 12 (construction entities, by function and form, respectively) Level 3 titles. *Technical and functional requirements*: compatibility shall be evaluated by comparing requirements and noting any discrepancies that could affect the ability to make useful conclusions; e.g., differences in technological and/or functional representativeness. *Pattern of use*: compatibility shall be evaluated by comparing the patterns of use and noting any discrepancies that could affect the ability to make useful conclusions; e.g., differences in occupant densities. *Required service life*: buildings shall at minimum be both considered either “permanent” or “temporary” structures.
17.2	The same *reference unit* shall be used, as calculated according to the same methodology, per Section 2.2.
17.3	The same information modules shall be included in the *system boundary*, along with the same activities enumerated in Appendix C, per Section 2.3. An exception is comparison of new construction to a refurbishment project.
17.4	The same *reference study period* shall be used, per Section 2.4.
17.5	The same *building model scope* shall be used; i.e., level 3 titles from OmniClass Table 21 (Elements), per Section 2.5.
17.6	The same *scenarios* and assumptions shall be used when identical activities happen to the buildings; e.g., the same construction processes result in the same fuel usage, per Section 3.
17.7	The same *flow types* should be selected for products, energy carriers, etc. when the specifications are the same across different buildings, per Section 4.1.
17.8	The *data quality of flows* the assessments draw on should generally be similar, per Section 4.3; a rationale should be provided if there are large differences (e.g., in flow accuracy).
17.9	The same sets of environmental data shall be used when different buildings consume the same resources (products, energy carriers, etc.), per Section 5.1
17.10	The *data quality of environmental information* the assessments draw on should generally be similar, per Section 5.2; a rationale should be provided if there are large differences (e.g., in representativeness).
17.11	*Environmental indicators* shall be calculated according to the same LCIA method, per Section 6.1.

Guidelines 17: Comparing two or more buildings	
17.12	*Biogenic carbon* and *carbonation* should only be considered if included in all assessments, and reported according to ISO 21930:2017 requirements.
17.13	*Reporting* shall include the same sets of indicators required to meet the purpose of the study, per Section 7.
17.14	A rationale shall be provided for any deviations from these guidelines.

6.4.4. Drawing conclusions and understanding limitations

Drawing conclusions from wbLCA results should be moderated with a recognition of the limitations and uncertainties of the study.

LCA is a predictive science with inherent uncertainties due to the necessity of making assumptions about the future. In addition, there are typically gaps in the underlying material and energy data and variations in data quality. And there is uncertainty in the characterization factors that impact assessment methods use to calculate impact indicators (which is why they are called “potential” impacts). Therefore, LCA is used as an estimating tool rather than a tool for precise measurement. Accordingly, when applied to building design, wbLCA results are best used to inform but not dictate design decisions.

A wbLCA study that is not truly the “whole” building may be missing significant impacts. A wbLCA study with an incomplete or inaccurate bill of materials may lead to misinterpretation of results. Whole-building LCA results from one study are not generalizable to other buildings. Whole-building LCA does not capture all environmental impacts of potential interest.

Assessing and communicating uncertainty is an important aspect of LCA; this is commonly addressed in product LCA but is not yet widely practised in LCA for construction works[22]. This is a topic requiring further work. In the meantime, wbLCA results should be used with an understanding of the limitations and communicated with transparent disclosure about limitations.

[22] S Saxe et al. 2020. Taxonomy of uncertainty in environmental life cycle assessment of infrastructure projects. Environ Res Lett 15:8.

7. Reporting and communication

A wbLCA report is the means by which an assessment is communicated. Depending on the intended use of the assessment, the report structure may be a summary and informal in nature, or it may communicate in detail all information required to assess the quality of the results and perhaps to reproduce the assessment. Approach to reporting for each of the three intended uses for wbLCA is characterized as follows:

- *Informing design*: the assessor is free to choose the depth of reporting and will tailor this to the communication needs for the project.
- *Meeting requirements*: the depth of reporting and perhaps a reporting template is established by the policymaker.
- *Performance declaration*: a report with maximum detail and transparency, written in accordance with the guidelines below, is recommended for a public declaration.

EN 15978:2011 Clause 12 requires extensive reporting of all aspects of the study and the detailed results and provides an example template. The EN 15978 requirements are interpreted and extended in Guidelines 18.

Guidelines 18: Reporting	
18.1	Additional information may be reported if it suits the purpose of the assessment. See other guidelines in this document for additional reporting best-practice.
18.2	These requirements may be waived if the wbLCA results will not be communicated to a third party and/or if reporting is not required to meet the purpose of the assessment.
18.3	If the purpose of the assessment is for a “performance declaration,” the report shall also be prepared in accordance with ISO 14044 Clause 5.2 and it shall be noted that the assessment is not intended to support comparative assertions.
18.4	Benchmarks (see Section 9) shall meet the reporting requirements of Guidelines 20.
General information on the assessment	
18.5	Purpose of the assessment shall be stated. At minimum, this should indicate “informing design,” “meeting requirements,” or “performance declaration.” Further detail should be provided, if appropriate; e.g., name of the program or policy if “meeting requirements.”
18.6	Building identification shall be stated and should at minimum include the building address.
18.7	The organization or individual that commissioned the assessment shall be identified; at minimum the client name. Contact information may also be provided.

Guidelines 18: Reporting	
18.8	Name(s) and qualification(s) of the assessor(s) shall be listed. This should include individuals that have been involved with compiling the bill of flows, calculation of results and report writing. Contact information may also be provided.
18.9	The assessment method, including version number, shall be identified. If an LCIA method other than TRACI v2.1 is used, a rationale should be provided.
18.10	EN 15978 requires a statement for the period of validity of the assessment; however, no methodology exists to establish such a period and this requirement may be complied with or waived at the discretion of the assessor. If a building substantially changes from what was originally modeled, the results may no longer be valid.
18.11	The date of the assessment shall be stated, and should be based on the day the LCIA is performed.
18.12	It shall be noted whether verification has occurred and what verification covers. When relevant, the name and qualification of the verifier shall be identified; contact information may also be provided.
General information on the object of assessment	
18.13	The functional equivalent shall be reported and should meet the requirements of Guidelines 2.
18.14	The reference unit(s) shall be reported and should meet the requirements of Guidelines 3.
18.15	The system boundary shall be reported and should meet the requirements of Guidelines 4.
18.16	The reference study period shall be reported and should meet the requirements of Guidelines 5.
18.17	The building model scope shall be reported and should meet the requirements of Guidelines 6.
Statement of the boundaries and scenarios used in the assessment	
18.18	The scenarios used to model the life cycle shall be provided. This may be waived if this information is embedded as default data in the software tool used and is publicly available for viewing; in that case, a reference to the software and version number may be provided. Deviations from software defaults should be noted in the report.
Data sources	
18.19	Information on the sources, type and quality of data used shall be provided. This may be waived if this information is embedded as default data in the software tool used and is publicly available for viewing; in that case, a reference to the software and version number may be provided. Deviations from software defaults should be noted in the report.

Guidelines 18: Reporting	
List of indicators used for assessment and expression of results	
18.20	The results for each environmental indicator shall be provided as a structured list for each module. If indicators or information modules are omitted, results should be marked as INA (indicator not assessed) and/or MNA (module not assessed). Reasons for any missing information shall be provided; e.g., lack of data, lack of data quality, or the information is not required to meet the purpose of the assessment.
18.21	If any module contains only partial information, this shall be clearly stated and reasons for omitting this information shall be given. This requirement may be waived provided the system boundary is defined according to the taxonomy presented in Appendix C and the reasons for omitting the information is reported. Omissions of life cycle activities from modules may be due to a lack of data, lack of data quality, or are not required to meet the purpose of the assessment.
18.22	Significant aspects may be reported, where relevant, as additional environmental information. This information may be either quantitative or qualitative, shall be verifiable, and may include LCA measures still under development, such as, but not limited to: – climate effects of delayed emissions (resulting from stored biogenic carbon or other processes) in the quantification of GWP, – land use-related impacts, or – toxicological aspects related to human health and/or the environment.

8. Verification

Verification is the process whereby an individual other than the assessor evaluates the quality of a wbLCA. This may be an individual that is internal to an organization or project or is external (third party) to it. EN 15978:2011 Clause 13 does not stipulate a mandatory verification procedure (i.e., it is optional); however, the standard does provide the following minimum requirements for the verification of results:

a) consistency between the purpose of the assessment and boundaries and scenarios used,

b) traceability of data used for the products,

c) conformity of data with ISO 21930[23],

d) consistency between the scenarios that apply at building level with those used for product data, and

e) completeness and justification of completeness for the quantification at the building level.

Guidelines 19: Verification of results	
19.1	Verification is optional unless otherwise indicated in these guidelines.
19.2	At minimum, verification should check for: alignment of the study (boundary, scenarios, etc.) with the stated purpose; traceability of data for products and alignment of data with ISO 21930:2017; consistency of scenarios across products and the building; and completeness.
19.3	Verification shall be performed if expressly required to meet the purpose of the assessment.
19.4	Verification should be performed if the purpose of the assessment is a “performance declaration.”
19.5	Verification may be internal or external to the project team and shall be undertaken by an expert independent of the wbLCA.
19.6	If the purpose of the assessment is to make a public comparative assertion, the requirements set out in ISO 14044:2006 [22] for third-party verification shall be followed and is outside the scope of these guidelines.

[23] Note: EN 15978 references EN 15804 in lieu of ISO 21930.

9. Benchmarking

Whole-building LCA is often used in a comparative context: a proposed building design is compared to a reference point (a benchmark). A benchmark is a set of wbLCA results to which a building of study can be compared. See Figure 19 for an example. While this application of LCA is common in green building programs and policy, where a building may be required to show improvement over a reference building or to meet some other performance target, it is not addressed in EN 15978.

Benchmarking requires special considerations to ensure derivation of the benchmark and comparison to it is valid. ISO 21678:2020 provides a framework for this.

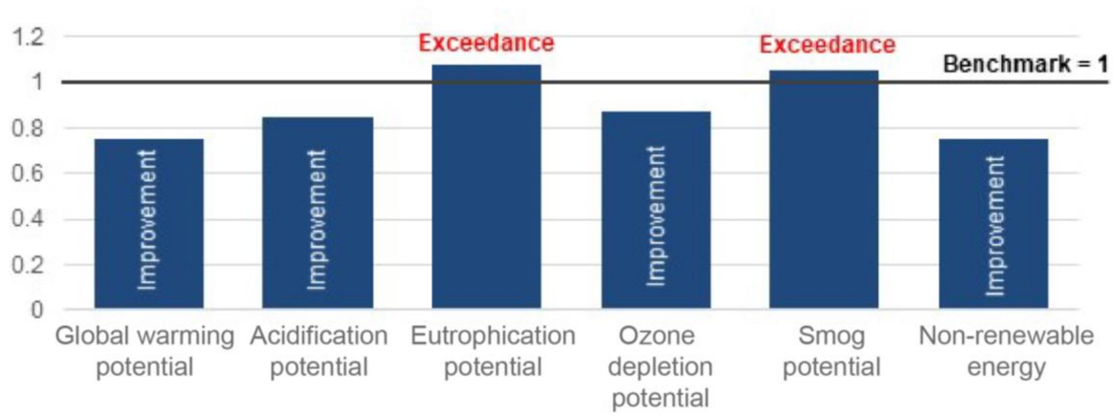

Figure 19: Comparing a building of study to a benchmark

In its rationale, ISO 21678:2020 anticipates an increasing need for sustainability benchmarks that will be used for target setting, to guide design decisions, in certification programs, and for communication. To support that need, this standard "defines principles, requirements and guidelines for the development and use of benchmarks." It is a framework for development of benchmarking methods (how to establish a benchmark and compare to it) and for development of programs or policy that include benchmarking.

The guidance in this section is in conformance with the framework put forth in ISO 21678. As noted in the standard, "transparent methods and common principles are needed for the development of benchmarks." In addition, the standard notes that benchmarks will vary by building type and region (clause 4.1). The standard repeatedly refers to statistical information as a basis for deriving benchmarks and specifies that "the data set shall be of a sufficient size to ensure the validity of a benchmark" (clause 5.2). These key points form the basis for the guidance provided here.

The standard defines three types of performance benchmark values:

a) Limit value: a minimum performance level that is set in recognition of current construction practice and feasibility of the limit value.

b) Reference value: a performance level that represents state of the art or best practice, as derived from statistical or survey data, a theoretical (reference or archetype) building, or a demonstration project.

c) Target value: a performance level that goes beyond the reference value. The determination is typically a policy decision but should be cognisant of current construction practice and feasibility of the target value.

These values represent different technology coverages (performance levels). Benchmarks also need to represent different time periods (vintages) and different geographic coverages (locales). In addition, benchmarks are selected or derived based on the purpose of the assessment. This means that no single set of results can apply in all situations.

The standard identifies multiple sources of information that might be used to determine a performance benchmark value (clause 4.2.4), including surveys and statistics for building design and construction. A sample set of such data, in alignment with the purpose of the benchmark and representative of the building of study (geographical, temporal and technology context, functional equivalence, etc.), can be the basis for deriving a benchmark. In these guidelines, this is defined as a *statistical benchmark* (Section 9.1).

Other sources of information identified in the standard that directly assist in development of valid benchmarks include “demonstration projects” and “theoretical calculations” (e.g., a reference building or an archetype). In other words, this is the use of a single building to derive the benchmark. In these guidelines, this type of benchmark is defined as a *baseline* (Section 9.2).

The standard emphasizes that development of benchmarks must be valid and that such development must be reported transparently. Clause 5.2 lays out specific rules for what should be reported about a benchmark, to validate it and to ensure functional equivalence. Clause 5.2 also states what must be reported about LCA system boundary and method when comparing to a benchmark.

Guidelines 20: Benchmarks	
20.1	Benchmarks produced in accordance with this document may be used for the purpose of evaluating the relative impacts of a building of study, provided the representativeness and functional equivalent of the benchmark supports the purpose of the assessment and the requirements of Guidelines 17 for comparison are met. wbLCA results for a benchmark and a building of study may be normalized on an external gross floor area basis for comparison purposes.

Guidelines 20: Benchmarks	
20.2	Benchmarks shall at minimum be declared and reported in accordance with ISO 21678 Clause 5.2 (items A01-A07, B01-B04 and C01-C02). The benchmark bill of materials per Guidelines 8 should also be reported. Reporting requirements may be waived if the information is available in other publicly available literature or is the same as the building of study and referenced in the wbLCA report. Reporting requirements may also be waived if the wbLCA results will not be communicated to a third party and/or if reporting is not required to meet the purpose of the assessment.
20.3	ISO 21678 Clause 5.2, A01: the reported benchmark indicator(s) and unit(s) shall be listed.
20.4	ISO 21678 Clause 5.2, A02: the technological representativeness of the benchmark shall at minimum be characterized as a “limit”, “reference” or “target” value, as defined in ISO 21678 Clause 4.2. A rationale should be provided for the declared technological representativeness (e.g., a “limit value” based on meeting but not exceeding building code minimums).
20.5	ISO 21678 Clause 5.2, A03 and A04: the benchmark’s functional equivalent shall be reported, and should be per Guidelines 2 to the extent possible and/or reasonable, and at minimum meet the requirements of Guidelines 2.2 and 2.6. A range of required service life may be declared (e.g., 50–65 years).
20.6	ISO 21678 Clause 5.2, A05: reference unit(s) shall be reported per Guidelines 3.
20.7	ISO 21678 Clause 5.2, A06: the geographic representativeness (locale) of the benchmark shall be provided and should by default be the municipality of the building(s). A rationale should be provided when the geographic boundary is a region (e.g., a county, province/state, country, etc.) or when the benchmark is based on a theoretical building.
20.8	ISO 21678 Clause 5.2, A07: the representativeness of the benchmark’s time period (vintage) shall be provided and should be based on the year(s) of initial construction or major renovation. A time range indicating vintage (e.g., 2010–2020) may be provided for this purpose. A rationale should be provided for the vintage of theoretical buildings (e.g., same as building of study since it’s an alternative design).
20.9	ISO 21678 Clause 5.2, B01: the LCIA and/or relevant inventorying method(s) used to calculate indicator results shall be listed. Information on the sources of environmental data used shall also be provided. This may be waived if this information is embedded as default data in the software tool used and is publicly available for viewing; in that case, a reference to the software and version number may be provided. Deviations from software defaults should be noted in the report.
20.10	ISO 21678 Clause 5.2, B02: The reference study period shall be reported. The scenarios used to model the life cycle shall also be provided. This may be waived if this information is embedded as default data in the software tool used and is publicly available for viewing; in that case, a reference to the software and version number may be provided. Deviations from software defaults should be noted in the report.

Guidelines 20: Benchmarks	
20.11	ISO 21678 Clause 5.2, B03: the building model scope of the benchmark should be reported per Guidelines 6.
20.12	ISO 21678 Clause 5.2, B04: the system boundary of the benchmark should be defined per Guideline 4.1.
20.13	ISO 21678 Clause 5.2, C01: the following on the source of information shall be provided: a) the state of project and available information (i.e., the accuracy of the building model(s)) per Guideline 10.8, b) the number of buildings used to derive the benchmark, c) any standards, policies or other methods used to calculate the benchmark, including this guidelines document, and d) if relevant, the database or library the benchmark was drawn from.
20.14	ISO 21678 Clause 5.2, C02: the type of information of the benchmark should be reported according to the options listed in Table 1 of ISO 21678.

9.1. Statistical benchmarks

Performance benchmarking in the building sector is typically associated with energy and water use in the operation of buildings. The concept of resource consumption accounting can similarly be applied to material use to create a mechanism for wbLCA performance benchmarks [14, 15]. This section provides explanation and guidance for wbLCA benchmarking keyed to statistical averages for material use.

Common indicators for building resource consumption are *energy use intensity* (or *EUI*; e.g., MJ per m^2 gross floor area per year) and *water use intensity* (or *WUI*; e.g., L per m^2 gross floor area per year). An analogous indicator for the consumption of materials can be identified: *material use intensity* (or *MUI*). An MUI is a compilation of the materials that comprise a building, identified as quantities per unit of gross floor area (for example, 1.05 m^3 concrete per m^2 of floor area, 0.010 tonnes steel/m^2, etc.). This would complete the set of resource consumption indicators.

EUIs, WUIs and MUIs may reflect the resource consumption of a single building or a statistical benchmark value from a sample set of buildings. The MUI benchmarks referred to in this document are mean material use quantities of constructed buildings.

See Figure 20 for an illustration of the three resource streams and their combined application in creating a complete wbLCA benchmark.

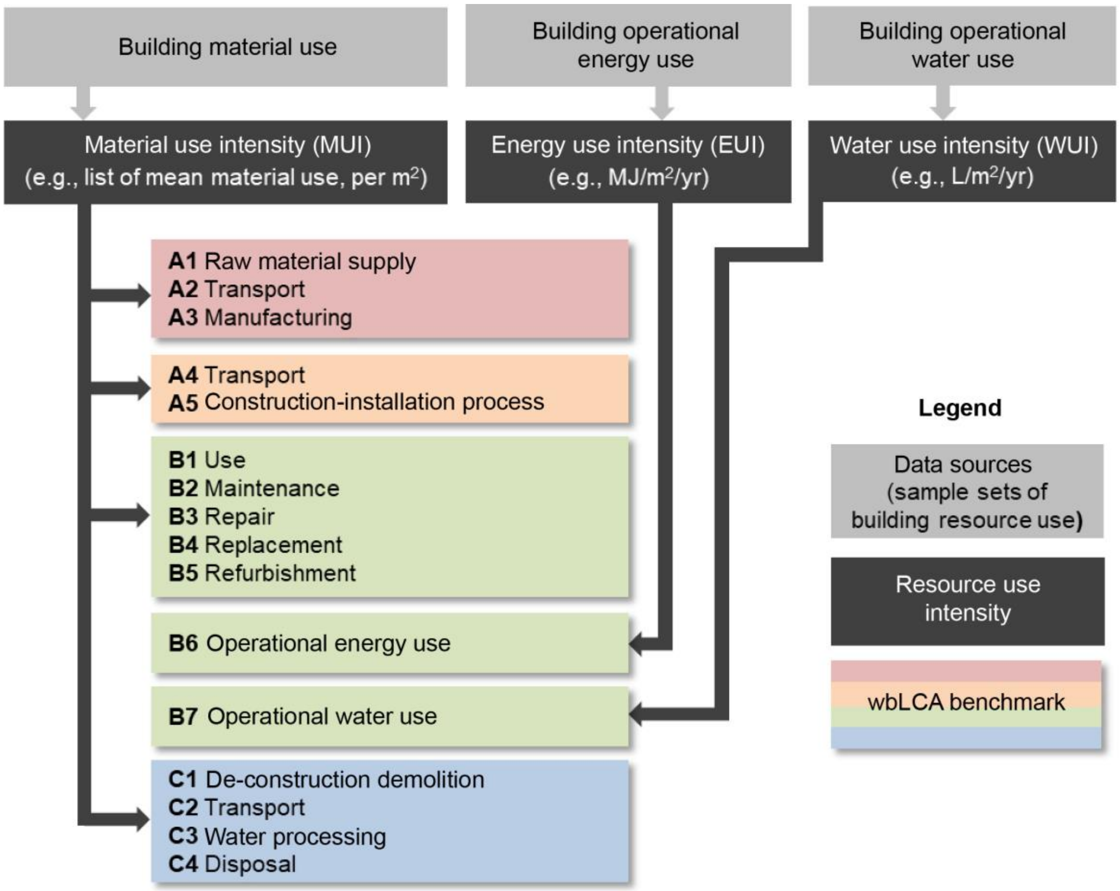

Figure 20: Resource use streams and wbLCA benchmarks

Energy use (EUI) and water use (WUI) benchmarks may already be available. A material use (MUI) benchmark is needed to complete the inputs for a model to run through a wbLCA tool and produce benchmark wbLCA results.

Determining a valid MUI benchmark requires consideration of representativeness and functional equivalence. This can be addressed if a large database of bills of materials is available, which can then be sampled for a subset of functional equivalents for the building of study, and then those MUIs are averaged for a MUI benchmark appropriate for the building of study.

The representativeness of the MUI benchmark must be well defined, as described in Section 9.

See Figure 21 for a representation of how this system would function. The material quantities for many buildings are available in a database and drawn on for an average MUI relevant for the building of study. This MUI is used to create a “peer” model for the building of study, to be assessed in wbLCA for the benchmark wbLCA results that will be a point of comparison for the building of study.

This approach to benchmarking enables maximum flexibility for application across different wbLCA uses, scopes, software tools, and policy implementations[24].

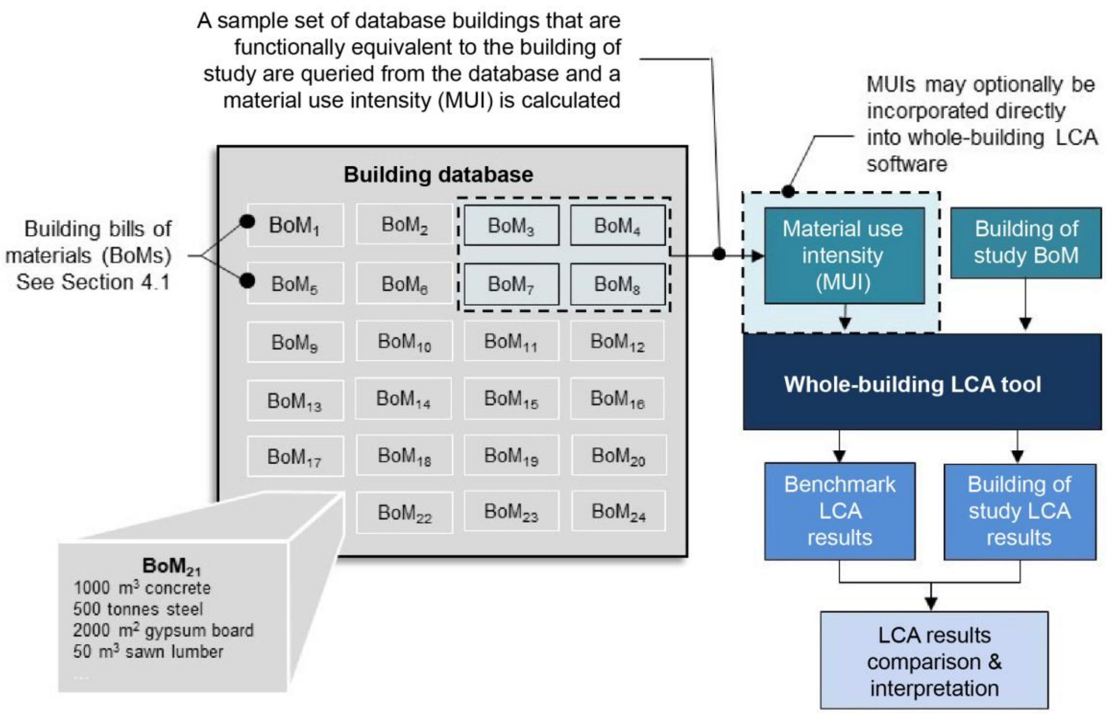

Figure 21: The MUI approach to wbLCA benchmarks

Consistency and clarity are important considerations when compiling the material use of different buildings. This suggests the need for a well-considered classification system to standardize the naming of building products and their allocation to different parts or systems of the building.

A method for quantifying and labeling materials is shown in Table 8. In this method, there is a hierarchy of information. Each material quantity ("product flow," in LCA terminology) of a building is assigned the following set of identifiers: an element from OmniClass Table 21 (i.e., UniFormat); a work result from

[24] An alternative approach to benchmarking involves collecting and averaging wbLCA results from a sample set of buildings. This is difficult to implement, because wbLCA studies can vary widely (depending on software, data, scope, etc.) and are therefore not likely to be comparable and averageable. In addition, comparability depends on building type, considerations of what comprises typical construction practice, regionality, and other factors. Instead, using material quantities as the basis for the approach maximizes the flexibility and dynamic capacity of the system. This approach accommodates the use of any wbLCA tool, any scope, any building type, and so forth. The system additionally will self-update to current practice as more buildings are added to the database. Data validation of material quantities is also simpler than with wbLCA results, because there are fewer parameters to check for inconsistencies.

OmniClass Table 22 (i.e., MasterFormat); and a product flow type, which has a unit. The resulting list of quantities is referred to as a "bill of materials". See Section 4.1 for more information on this topic.

A standard method for deriving benchmarks with statistically representative technology, geographic coverage and time span is not yet established and is an area of research. Future editions of this document will address this as new information emerges.

Table 8: A standardized method for material quantity labeling

Data type	Description	Example
Element	Each quantity is assigned a Level 3 title from OmniClass Table 21. By including/excluding elements, customized benchmarks can be produced.	[01 40 10] Standard Slabs-on-Grade
Work result	Each quantity is assigned a Level 3 title from OmniClass Table 22 (see section 4.1) and enables contribution analysis of results by elements.	[03 21 11] Plain Steel Reinforcement Bars
Product flow	Flows are named for common building product types, based on material standards; naming may include product grades, thicknesses, etc.	regular (R) steel, 400 MPa, CSA G30.18-09 (R2019)
Unit	The standard unit of measure for the type of flow.	tonnes

Guidelines 21: Statistical benchmarks

21.1 Statistical benchmark wbLCA environmental indicator results produced in accordance with the Guidelines shall be based on a material use intensity (MUI) benchmark. The MUI shall have a defined building model scope per Guidelines 6 and be derived from a sample set of building bill of materials (Section 4.1).

The MUI shall be calculated as follows.

For each element (OmniClass Table 21, Level 3) included in MUI building model scope:

a) across the buildings in the sample set, sum the quantity of each product for each work result (OmniClass Table 22, Level 3),

b) sum the external gross floor areas of all buildings whose bill of materials similarly includes that element in building model scope, and

c) divide the product quantity totals from a) by the total external gross floor area from b).

The result is the mean quantities of products, for each element and work result, per unit external gross floor area. Should this degree of granularity not be required, product quantities may be summed across elements and/or work results.

21.2 Bills of materials used in MUI benchmarks shall be derived from a set of constructed buildings, shall meet the requirements of Guidelines 8 and 10.8, and shall include the following additional information:

Guidelines 21: Statistical benchmarks	
	a) the external gross floor area, calculated in accordance with the method presented in Appendix A, b) the building location (city, province/state and country), c) date of construction (year), d) the functional equivalent, per Guidelines 2, e) the building model scope, per Guidelines 6, and f) the state of project and available information, as classified in Guideline 10.8. Bills of materials should include the following additional information: a) the name(s) and contact information of the individual(s) responsible for quantifying the bill of materials, b) the date the bill of materials was completed (year), c) other reference unit(s) applicable to the building, per Guidelines 3, d) how the bill of materials was derived from the building model; e.g., BIM, cost report, takeoff software, etc., e) a data quality assessment per Guidelines 10, f) identification of any quantities that come from secondary sources (e.g., from other projects or industry-average), and g) a statement that the bill of materials has been compiled in accordance with this document.
21.3	The buildings used to derive an MUI benchmark shall be selected on the basis of functional equivalents (Section 2.1), year of construction and location, with consideration of the representativeness required to meet the intended use of the benchmark. Buildings shall have a similar degree of accuracy, as defined by Guideline 10.8.
21.4	ISO 21678 Clause 5.2 item A06: A statistical benchmark's geographical coverage (locale) should by default be based on the municipality which constituent buildings are located. When buildings in the sample set are located in more than a single municipality, the geographic boundary may be expanded to the next smallest region type (e.g., a county, province/state, country, etc.), that encapsulates the buildings in the sample set.
21.5	Benchmarks derived from a sample set of wbLCA results may also be considered in conformance with this document provided the requirements of Guidelines 17 on comparison are met, for all buildings in the sample set.

9.2. Baselines

The reference point traditionally used for wbLCA comparisons is a baseline. As defined here, a baseline is the wbLCA results for a specific single building. A baseline generally remains set over a phase of design. The baseline building may be the starting point for the design of the building of study; for example, a “reference building” that the building of study must improve upon in meeting requirements as in the wbLCA provisions in some green building programs.

Baselines can be representative of different performance levels and can be derived from different sources. Here are the common options for deriving a baseline:

- *Early design iterations*. An early version of the building design is set as the baseline to track the performance of the building of study as it evolves.
- *Alternative designs*. A different design for the building of study is used as the baseline. In this approach, the project team may have significant additional work in designing the alternative building.
- *Existing buildings*. An existing peer building with sufficient information available to derive the necessary quantities for wbLCA is set as the baseline.
- *Archetypes*. An existing or theoretical “typical” building is set as the baseline. In this approach, it’s important to be mindful of archetypes that are overly simplified or idealized.

In all cases, the accuracy and functional equivalency of the assessments may need to be addressed over the course of design, and adjustments may be needed to maintain a baseline with consistent scope and methods to the building of study.

When using wbLCA to inform design, assessors are free to select any baseline, provided they are careful about the conclusions they make. In contrast, when using wbLCA to meet third-party requirements, assessors will typically follow substantial instruction on what qualifies as a baseline, since it is the reference point from which compliance is evaluated[25].

Guidelines 22: Baselines	
22.1	A baseline shall be a single building that is either a theoretical design (e.g., an archetype) or a constructed building.
Guidelines for setting baselines when “meeting requirements”	
22.2	The design should be feasible and constructible.
22.3	The following design aspects should be reasonably similar to the building of study: a) architectural complexity, b) number of above-grade and below-grade floors (e.g., 5 vs. 50 floors not acceptable), c) floor heights (e.g., 3.5 m vs. 5.5 m floor height not acceptable), d) design features (e.g., open-concept spaces), and

[25] The ASCE/SEI *Guide to Definition of the Reference Building Structure and Strategies in Whole Building Life Cycle Assessment* [13] provides complementary guidance to this document on the development and use of baselines in wbLCA practice.

Guidelines 22: Baselines	
	e) allowance for the size of structure (e.g., beam depth).
22.4	Relative to the building of study, the building geometry of the design should not excessively: a) reduce the capacity to produce a reasonably efficient structure, b) increase snow or overturning loads, or c) increase operational energy demand.
22.5	The building footprint of the design should provide sufficient site area for the project's external works.
22.6	Structural design unique to the baseline should have the following attributes reflecting typical practice: a) a predicted service life equal to, or greater than, the building service life, b) spans generally within accepted useful ranges, c) a layout that transfers loads to the foundation in a reasonably efficient manner, and d) a foundation system that is appropriate for the geotechnical conditions of the project site and the supported loading.
22.7	The enclosure design unique to the baseline should reflect typical practice and reasonably efficient use of constituent materials.
22.8	The total linear length of interior partitions (i.e., fixed + movable + glazed) and/or associated number of doors should be either: a) the same as the building of study design (early or final design iteration), or b) the same as that of an existing building available to the project team, over an equivalent gross area, serving the same function.
22.9	The design should comprise materials, assemblies and service systems that are considered contemporary, available and reasonably economical for the project location.
22.10	Relative to the building of study, the baseline design should not include materials, assemblies and service systems that have been used in an unconventional manner.
22.11	Relative to the building of study, the design should not exhibit arbitrary, excessive material use, including: a) over-sized structural elements and non-structural materials, b) material use in excess of what is needed to meet fireproofing, sound attenuation, vibration, and other performance requirements, and c) redundant material use.

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Appendix A – Method for calculating gross floor area

The source for this method is *Elemental Cost Analysis: Measurement of Buildings by Area & Volume*, Canadian Institute of Quantity Surveyors (CIQS) (2006) [16].

Definitions

Enclosed
Any space which is surrounded by permanent materials applied to vertical or horizontal surfaces for the purpose of weatherproofing to acceptable occupational standards.

Enclosing wall
Those walls which form the outside perimeter of the structure and are made of permanent materials which provide weatherproofing to acceptable occupational standards.

Gross area
The total area for each building as measured in accordance with the principles laid down in this publication.

Outside face
The exterior face of an enclosing wall at floor level, excluding horizontal features such as projecting cornices, stone bands, etc.

Method

Measure the outside face of enclosing walls for the area on each floor without any deductions for openings within the floor area, except as noted later. When the enclosing walls are broken up with a large number of small projections (e.g., projecting columns), the measurements shall be taken to the mean face of the enclosing walls.

General notes

1. As a general rule the areas included must be fully enclosed.
2. No deductions to the area shall be made for:
    a. walls, partitions, etc.,
    b. openings in floors for stairwells, escalators, elevators, ducts and other facilities,
    c. pits, trenches and depressions occurring in the lowest floor which are open or have removable covers,
    d. columns, piers or pilasters, and
    e. any other features within the confines of the perimeter walls.
3. Where auditoriums, swimming pools, gymnasiums, foyers and the like extend through two or more floors, they shall be included for the largest area, at one level only.

Inclusions

The following items shall be included in computing the gross floor area:

- crawl spaces with concrete floors which have a floor-to-ceiling height that is 2 m or greater,
- basement areas with a floor-to-ceiling height of 2 m or greater,
- future basement areas with a floor-to-ceiling height of 2 m or greater, where only the concrete slab on grade is required for structural completion,
- floor areas which are structurally completed and where the finish work will be executed at a later date,
- tunnels, trenches, etc., which have a roof slab that is 2 m or more from the floor,
- rooms below grade or sidewalk; e.g., transformer rooms,
- duct shafts, columns and the like projecting beyond the general face of the enclosing walls, provided they extend vertically for the full floor height,
- dormers, bay windows and the like, provided they extend vertically for the full floor height,
- penthouses,
- elevator machine floors within penthouses,
- connecting links or walkways, provided they are enclosed,
- finished rooms in roofs and attics,
- attached garages above and/or below ground level,
- enclosed exterior staircases and fire escapes,
- enclosed porches, and
- balconies and mezzanines which are within the enclosing walls of the structure.

Exclusions

The following items shall be excluded in computing gross areas. However, if certain conditions warrant the inclusion of some of these items, they shall be listed separately from the gross area:

- crawl spaces which do not have concrete floors and which have a floor height of less than 2 m,
- tunnels, trenches, etc. with less than 2 m head room,
- exterior balconies,
- canopies,
- projections beyond the face of the enclosing walls which do not extend vertically for a full floor height,
- prefabricated doghouses on roofs,
- connecting links which are not enclosed,

- unfinished roof and attic areas,
- carports,
- exterior staircases and fire escapes which are not enclosed,
- isolated chimneys and that portion of chimney above the roof line,
- interior open courtyards, light wells and the like,
- porches which are not enclosed,
- exterior steps and landing,
- exterior paving, patios and terraces,
- areas which are enclosed with perimeter walls but not with a roof, and
- roof overhangs and cornices.

Appendix B – Building model scope definition

Table 9 below can be used to define the building model scope (see Section 2.5) of an assessment. For most practitioners, a much-reduced subset of the list will suffice when presenting the scope in a report. The table lists each element title, along with its Level 3 UniFormat and OmniClass Table 21 codes. There are three additional columns to identify how the title affects the system boundary and/or reporting for material use, operational energy use and operational water use.

Table 9: Building model scope definition

Notes for the table: The information presented in the three columns labeled “System boundary relevance” is an interpretation of EN 15978:2011 reporting requirements, in particular with respect to OE and OW, as described in Section 2.3 (see the legend below). The columns are colour-coded: green cells are those elements that are required to be reported with primary results; yellow cells are results that should be reported separately from the primary results; and red cells do not include relevant results for reporting.

Legend:

M = material use

OE = operating energy use

OW = operating water use

A = the M, OE or OW system consuming energy/water is building- or site-integrated and should be reported *with* primary results (highlighted green).

B = there is little-to-no M; however, this element contributes to the system boundary and is not otherwise associated with a product. Should be reported *with* primary results (cell is shaded green).

C = the OE or OW system consuming energy/water is building- or site-integrated and should be reported *separately* from primary results *or* the M, OE or OW system consuming energy/water is not building- or site integrated and should be reported *separately* from primary results (cell is shaded yellow).

N = does not include relevant M, OE or OW (cell is shaded red).

UniFormat number	OmniClass number	Title	System boundary relevance		
			M	OE	OW
A	01 00 00	Substructure			
A10	01 10	Foundations			
A1010	01 10 10	Standard Foundations	A	N	N
A1020	01 10 20	Special Foundations	A	N	N
A20	01 20	Subgrade Enclosures			
A2010	01 20 10	Walls for Subgrade Enclosures	A	N	N
A40	01 40	Slabs-On-Grade			
A4010	01 40 10	Standard Slabs-on-Grade	A	N	N
A4030	01 40 20	Structural Slabs-on-Grade	A	N	N
A4040	01 40 30	Slab Trenches	A	N	N
A4040	01 40 40	Pits and Bases	A	N	N

UniFormat number	OmniClass number	Title	System boundary relevance		
			M	OE	OW
A4090	01 40 90	Slab-On-Grade Supplementary Components	A	N	N
A60	01 60	Water and Gas Mitigation			
A6010	01 60 10	Building Subdrainage	B	N	N
A6020	01 60 20	Off-Gassing Mitigation	B	N	N
A90	01 90	Substructure Related Activities			
A9010	01 90 10	Substructure Excavation	B	N	N
A9020	01 90 20	Construction Dewatering	B	N	N
A9030	01 90 30	Excavation Support	B	N	N
A9040	01 90 40	Soil Treatment	B	N	N
B	02 00 00	Shell			
B10	02 10	Superstructure			
B1010	02 10 10	Floor Construction	A	N	N
B1020	02 10 20	Roof Construction	A	N	N
B1080	02 10 80	Stairs	A	N	N
B20	02 20	Exterior Vertical Enclosures			
B2010	02 20 10	Exterior Walls	A	N	N
B2020	02 20 20	Exterior Windows	A	N	N
B2050	02 20 50	Exterior Doors and Grilles	A	N	N
B2070	02 20 70	Exterior Louvers and Vents	A	N	N
B2080	02 20 80	Exterior Wall Appurtenances	A	N	N
B2090	02 20 90	Exterior Wall Specialties	A	N	N
B20	02 30	Exterior Horizontal Enclosures			
B3010	02 30 10	Roofing	A	N	N
B3020	02 30 20	Roof Appurtenances	A	N	N
B3040	02 30 40	Traffic Bearing Horizontal Enclosures	A	N	N
B3060	02 30 60	Horizontal Openings	A	N	N
B3080	02 30 80	Overhead Exterior Enclosures	A	N	N
C	03 00 00	Interiors			
C10	03 10	Interior Construction			
C1010	03 10 10	Interior Partitions	A	N	N
C1020	03 10 20	Interior Windows	A	N	N
C1030	03 10 30	Interior Doors	A	N	N
C1040	03 10 40	Interior Grilles and Gates	A	N	N
C1060	03 10 60	Raised Floor Construction	A	N	N
C1070	03 10 70	Suspended Ceiling Construction	A	N	N
C1090	03 10 90	Interior Specialties	A	N	N
C20	03 20	Interior Finishes			

UniFormat number	OmniClass number	Title	System boundary relevance		
			M	OE	OW
C2010	03 20 10	Wall Finishes	A	N	N
C2020	03 20 20	Interior Fabrications	A	N	N
C2030	03 20 30	Flooring	A	N	N
C2040	03 20 40	Stair Finishes	A	N	N
C2050	03 20 50	Ceiling Finishes	A	N	N
D	04 00 00	Services			
D10	04 10	Conveying			
D1010	04 10 10	Vertical Conveying Systems	A	C	N
D1030	04 10 30	Horizontal Conveying	A	C	N
D1050	04 10 50	Material Handling	A	C	N
D1080	04 10 80	Operable Access Systems	A	C	N
D20	04 20	Plumbing			
D2010	04 20 10	Domestic Water Distribution	A	C	A C
D2020	04 20 20	Sanitary Drainage	A	C	A C
D2030	04 20 30	Building Support Plumbing Systems	A	C	A C
D2050	04 20 50	General Service Compressed-Air	A	C	N
D2060	04 20 60	Process Support Plumbing Systems	A	C	A C
D30	04 30	Heating, Ventilation, and Air Conditioning (HVAC)			
D3010	04 30 10	Facility Fuel Systems	A	A	N
D3020	04 30 20	Heating Systems	A	A	A
D3030	04 30 30	Cooling Systems	A	A	A
D3050	04 30 50	Facility HVAC Distribution Systems	A	A	A
D3060	04 30 60	Ventilation	A	A	A
D3070	04 30 70	Special Purpose HVAC Systems	A	C	C
D40	04 40	Fire Protection			
D4010	04 40 10	Fire Suppression	A	C	A
D4030	04 40 30	Fire Protection Specialties	A	N	N
D50	04 50	Electrical			
D5010	04 50 10	Facility Power Generation	A	A	N
D5020	04 50 20	Electrical Service and Distribution	A	A C	N
D5030	04 50 30	General Purpose Electrical Power	A	A C	N
D5040	04 50 40	Lighting	A	A	N
D5080	04 50 80	Miscellaneous Electrical Systems	A	A C	N
D60	04 60	Communications			
D6010	04 60 10	Data Communications	A	C	N

UniFormat number	OmniClass number	Title	System boundary relevance		
			M	OE	OW
D6020	04 60 20	Voice Communications	A	C	N
D6030	04 60 30	Audio-Video Communication	A	C	N
D6060	04 60 60	Distributed Communications and Monitoring	A	C	N
D6090	04 60 90	Communications Supplementary Components	A	C	N
D70	04 70	Electronic Safety and Security			
D7010	04 70 10	Access Control and Intrusion Detection	A	C	N
D7030	04 70 30	Electronic Surveillance	A	C	N
D7050	04 70 50	Detection and Alarm	A	C	N
D7070	04 70 70	Electronic Monitoring and Control	A	C	N
D7090	04 70 90	Electronic Safety and Security Supplementary Components	A	C	N
D80	04 80	Integrated Automation			
D8010	04 80 10	Integrated Automation Facility Controls	A	A	N
E	05 00 00	Equipment and Furnishings			
E10	05 10	Equipment			
E1010	05 10 10	Vehicle and Pedestrian Equipment	C	C	C
E1030	05 10 30	Commercial Equipment	C	C	C
E1040	05 10 40	Institutional Equipment	C	C	C
E1060	05 10 60	Residential Equipment	C	C	C
E1070	05 10 70	Entertainment and Recreational Equipment	C	C	C
E1090	05 10 90	Other Equipment	C	C	C
E20	05 20	Furnishings			
E2010	05 20 10	Fixed Furnishings	A	N	N
E2050	05 20 50	Movable Furnishings	C	N	N
F	06 00 00	Special Construction and Demolition			
F10	06 10	Special Construction			
F1010	06 10 10	Integrated Construction	A	N	N
F1020	06 10 20	Special Structures	A	N	N
F1030	06 10 30	Special Function Construction	A	N	N
F1050	06 10 50	Special Facility Components	A	N	N
F1060	06 10 60	Athletic and Recreational Special Construction	A	N	N
F1080	06 10 80	Special Instrumentation	A	N	N
F20	06 20	Facility Remediation			

UniFormat number	OmniClass number	Title	System boundary relevance		
			M	OE	OW
F2010	06 20 10	Hazardous Materials Remediation	B	N	N
F30	06 30	Demolition			
F3010	06 30 10	Structure Demolition	B	N	N
F3030	06 30 30	Selective Demolition	B	N	N
F3050	06 30 50	Structure Moving	B	N	N
G	07 00 00	Sitework			
G10	07 10	Site Preparation			
G1010	07 10 10	Site Clearing	B	N	N
G1020	07 10 20	Site Elements Demolition	B	N	N
G1030	07 10 30	Site Element Relocations	B	N	N
G1050	07 10 50	Site Remediation	B	N	N
G1070	07 10 70	Site Earthwork	A/B	N	N
G20	07 20	Site Improvements			
G2010	07 20 10	Roadways	A	A C	N
G2020	07 20 20	Parking Lots	A	A C	N
G2030	07 20 30	Pedestrian Plazas and Walkways	A	A C	N
G2040	07 20 40	Airfields	A	A C	N
G2050	07 20 50	Athletic, Recreational, and Playfield Areas	A	A C	N
G2060	07 20 60	Site Development	A	A C	N
G2080	07 20 80	Landscaping	A	A C	N
G30	07 30	Liquid and Gas Site Utilities			
G3010	07 30 10	Water Utilities	A	C	A C
G3020	07 30 20	Sanitary Sewerage Utilities	A	C	A C
G3030	07 30 30	Storm Drainage Utilities	A	C	A C
G3050	07 30 50	Site Energy Distribution	A	A	A
G3060	07 30 60	Site Fuel Distribution	A	A	N
G3090	07 30 90	Liquid and Gas Site Utilities Supplementary Components	A	A	N
G40	07 40	Electrical Site Improvements			
G4010	07 40 10	Site Electric Distribution Systems	A	A C	N
G4010	07 40 50	Site Lighting	A	A	N
G50	07 50	Site Communications			
G5010	07 50 10	Site Communications Systems	A	C	N
G90	07 90	Miscellaneous Site Construction			
G9010	07 90 10	Tunnels	A	N	N

Appendix C – Calculation of the environmental indicators

All calculations per Equation 4 (Section 6.1) required to report environmental indicator results for the complete system boundary according to EN 15978 are given in Table 10 below. The calculations involve multiplying environmental data by a quantity from the bill of flows to arrive at an environmental indicator result; for example:

$$\underbrace{250\ \text{kg}\ CO_2\ /\ m^3\ \text{concrete}}_{\substack{\text{environmental data}\\ \text{(Section 5.1)}}} \times \underbrace{100\ m^3\ \text{concrete}}_{\substack{\text{bill of flows quantity}\\ \text{(Section 4.2)}}} = \underbrace{25{,}000\ \text{kg}\ CO_2}_{\substack{\text{indicator result}\\ \text{(Section 6.1)}}}\ \text{(global warming potential)}$$

Indicator results are summed (denoted in the table with the symbol ∑) across the various environmental data/flow pairs that are relevant to the scope of the table row in question to arrive at the total indicator result for that row. For example, the indicator result above is added to similar calculations for other building products, to arrive at the total global warning potential due to materials production (information modules A1-A3).

The table details two ways to calculate environmental indicator results:

1. The darker-coloured rows are calculations based on *Method 3* (see Sections 4.2 and 5.1), involving environmental datasets with a functional unit. These calculations consist of a single equation at the information module level (A1-3, A4, A5, B1, etc.).
2. The lighter-coloured rows are calculations based on *Method 1* or *2* (see Sections 4.2 and 5.1), which account for the various “activities” that make up each information module and that in sum account for its environmental impact. The activities are given alphanumeric identifiers; e.g., the activities of module A4 Transport are A4.1, A4.2 and A4.3. Each activity is composed of one or more equations that in sum account for its environmental impact. They are further delineated with alphanumeric identifiers; e.g., the equations for activity A4.3 are A4.3.1, A4.3.2, A4.3.3, A4.3.4, and A4.3.5.

Compiling the bill of flows is typically the most time-consuming and complicated part of wbLCA practice. The four columns at the right of the table are intended to guide practitioners on data sources for deriving flow quantities. This information is structured according to the classification system described in Guideline 10.2.

Table 10: Calculation of the environmental indicators

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
A1-A3 Raw material supply, transport, manufacturing	**A1-A3** ∑ [**A1-A3** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	taken (measured) from, for example, a purchase order, purchase receipt, etc.	derived from the building model via BIM or quantity takeoff methods	calculated from quantities reported in an LCA/EPD or from the MUI of, for example, an archetype, existing design, design option	calculated from quantities of an industry-average source or calculated from an MUI benchmark
A1-A3.1 Cradle-to-gate construction products included in the building model scope	**A1-A3.1.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
A4 Transport	**A4** ∑ [**A4** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
A4.1 Transport of materials and products from the factory gate to the building site, including any transport, intermediate storage and distribution	**A4.1.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), for initial construction]	taken (measured) from, for example, a fuel bill	calculated from the transport modes (truck, rail, etc.) and transport distances (km) of a project	calculated from the transport modes (truck, rail, etc.) and transport distances (km) reported in an LCA/EPD or from quantities reported in an LCA/EPD	calculated from the transport modes (truck, rail, etc.) and transport distances (km) of an industry-average source or from quantities of an industry-average source

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
A4.2 Transport of construction equipment to and from the site	**A4.2.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of equipment *transport-energy* (MJ, t*km, L, etc.), for initial construction]	taken (measured) from, for example, a fuel bill	calculated from the equipment types and schedules, the transport modes (truck, rail, etc.), and the transport distances (km) of a project	calculated from quantities reported in an LCA/EPD	calculated from the equipment types and schedules, the transport modes (truck, rail, etc.), and the transport distances (km) of an industry-average source or from quantities of an industry-average source
A4.3 All impacts and aspects related to losses due to the transportation	**4.3.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), due to transport losses from initial construction]	measured by project team	estimated by project team based on project type, products used, etc.	calculated from the transport loss rate (e.g. 5%) reported in an LCA/EPD	calculated from the transport loss rate (e.g. 5%) of an industry-average source
	4.3.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), due to transport losses from initial construction]	sim. to **A4.1.1**, based on quantities from **A4.3.1**			
	4.3.3 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), due to transport losses from initial construction]	sim. to **C2.1.1**, based on quantities from **A4.3.1**			
	4.3.4 ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, due to transport losses from initial construction]	sim. to **C3.1.1**, based on quantities from **A4.3.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
	4.3.5 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, due to transport losses from initial construction]	sim. to **C4.1.1**, based on quantities from **A4.3.1**			
A5 Construction-installation process	**A5** ∑ [**A5** (functional unit)] × [quantity of **product** (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
A5.1 Installation of the products into the building	**5.1.1** ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *construction-energy* (MJ, L, kWh, etc.), for initial construction]	taken (measured) from, for example, a fuel or utility bill, energy meter	estimated by project team based on project information; e.g., construction equipment usage, fuel use rates	calculated from quantities reported in an LCA/EPD	calculated from, for example, construction equipment usage, fuel use rates of an industry-average source or quantities of an industry-average source
A5.2 Installation of temporary works	**A5.2.1** sim. to **5.1.1**	sim. to **5.1.1**			
A5.3 Provision of heating, cooling, ventilation, humidity control etc. during the construction process	**5.3.1** sim. to **5.1.1**	sim. to **5.1.1**			
A5.4 Provision of heating, cooling, ventilation, humidity control etc. for *temporary works* during the construction process	**5.4.1** sim. to **5.1.1**	sim. to **5.1.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] × [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
A5.5 Transport of materials, products, waste and equipment within the site	**5.5.1** sim. to **5.1.1**	sim. to **5.1.1**			
A5.6 Ground works and landscaping	**5.6.1** sim. to **5.1.1**	sim. to **5.1.1**			
A5.7 On-site production and transformation of a product	**5.7.1** sim. to **5.1.1**	sim. to **5.1.1**			
A5.8 Storage of products, including the provision of heating, cooling, humidity, etc.	**5.8.1** sim. to **5.1.1**	sim. to **5.1.1**			
A5.9 Water use for cooling of the construction machinery or on-site cleaning	**5.9.1** ∑ [*water use* (m^3)] × [quantity of *construction-water* (m^3), for initial construction]	taken (measured) from, for example, a water bill, water meter	estimated by project team based on project information; e.g., construction equipment usage, water use rates	calculated from quantities reported in an LCA/EPD	calculated from, for example, construction equipment usage, water use rates of an industry-average source or quantities of an industry-average source
	5.9.2 ∑ [*wastewater treatment* (m^3)] × [quantity of *construction-wastewater* (m^3), for initial construction]	taken (measured) from, for example, a wastewater treatment or transport bill	estimated by project team based on project information; e.g., construction equipment usage, water use and wastewater generation rates	calculated from quantities reported in an LCA/EPD	calculated from, for example, construction equipment usage, water use and wastewater generation rates of an industry-average source or quantities of an industry-average source

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
A5.10 Production, transportation and waste management of products and materials lost during the construction and installation process	**A5.10.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), due to construction losses, including transport losses]	measured by project team	estimated by project team based on project type, products used, etc.	calculated from the construction loss rate (e.g. 5%) and transport loss rate (e.g. 5%) reported in an LCA/EPD	calculated from the construction loss rate (e.g. 5%) and transport loss rate (e.g. 5%) of an industry-average source
	A5.10.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), for initial construction, due to construction losses, including transport losses]	sim. to **A4.1.1**, based on quantities from **A5.10.1**			
	A5.10.3 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), for initial construction, due to construction losses, including transport losses]	sim. to **C2.1.1**, based on quantities from **A5.10.1**			
	A5.10.4 ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, for initial construction, due to construction losses, including transport losses]	sim. to **C3.1.1**, based on quantities from **A5.10.1**			
	A5.10.5 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, for initial construction, due to construction losses, including transport losses]	sim. to **C4.1.1**, based on quantities from **A5.10.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] × [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
A5.11 Production and transport of ancillary materials not counted in products used for installation of products into the building	**A5.11.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), ancillary materials for initial construction, including due to transport and construction losses]	taken (measured) from, for example, a purchase order, purchase receipt, etc.	estimated by project team based on project type, products used, etc.	calculated from the ancillary material use rate (per unit product), construction loss rate (e.g. 5%) and transport loss rate (e.g. 5%) reported in an LCA/EPD	calculated from the ancillary material use rate (per unit product), construction loss rate (e.g. 5%) and transport loss rate (e.g. 5%) of an industry-average source
	A5.11.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), ancillary materials for initial construction, including due to transport and construction losses]	sim. to **A4.1.1**, based on quantities from **A5.11.1**			
A5.12 Production and transport for temporary works, including temporary works located off site as necessary for the construction installation process	**A5.12.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), temporary works for initial construction, including due to transport and construction losses]	taken (measured) from, for example, a purchase order, purchase receipt, etc.	estimated by project team based on project type, products used, etc.	calculated from the temporary works material use rate (per unit product), construction loss rate (e.g. 5%) and transport loss rate (e.g. 5%) reported in an LCA/EPD	calculated from the temporary works material use rate (per unit product), construction loss rate (e.g. 5%) and transport loss rate (e.g. 5%) of an industry-average source
	A5.12.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), temporary works for initial construction]	sim. to **A4.1.1**, based on quantities from **A5.12.1**			
A5.13 Waste management processes for ancillary materials and temporary works, and other wastes	**A5.13.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), ancillary materials and temporary works for initial construction]	sim. to **C2.1.1**, based on quantities from **A5.11.1** and **A5.12.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
generated on the construction site until final disposal or until end of waste state is reached	**A5.13.2** ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, ancillary materials and temporary works for initial construction]	sim. to **C3.1.1**, based on quantities from **A5.11.1** and **A5.12.1**			
	A5.13.6 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, ancillary materials and temporary works for initial construction]	sim. to **C4.1.1**, based on quantities from **A5.11.1** and **A5.12.1**			
A5.14 Impacts of the manufacturing of capital goods (e.g. trucks, cranes)	*Note*: only a fraction of the manufacturing of capital goods, based on the service life of the product and the building's construction, should be allocated to the building of study. This procedure is beyond the scope of this document.				
B1 Installed products in use	**B1** ∑ [**B1** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
B1.1 Emissions to and from products during use phase	**B1.1.1** ∑ [*product emissions* (declared unit, as a function of time)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
B2 Maintenance	**B2** ∑ [**B2** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] × [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
B2.1 The production and transportation of the components and ancillary products used for maintenance	**B2.1.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), for maintenance activities, including due to transport and construction losses]	taken (measured) from, for example, purchase orders, purchase receipts, etc., over a period of time	estimated by project team based on project type, products used, etc.	calculated from the maintenance rate (e.g., 5%), maintenance frequency (years), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) reported in an LCA/EPD	calculated from the maintenance rate (e.g., 5%), maintenance frequency (years), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) of an industry-average source
	B2.1.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), for maintenance activities]	sim. to **A4.1.1**, based on quantities from **B2.1.1**			
B2.2 The production and transportation of the ancillary products used for maintenance	**B2.2.1** ∑ [product use (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), ancillary materials for repair activities, including transport and construction losses]	taken (measured) from, for example, purchase orders, purchase receipts, etc., over a period of time	estimated by project team based on project type, products used, etc.	calculated from the maintenance rate (e.g., 5%), maintenance frequency (years), ancillary material use rate (per unit product), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) reported in an LCA/EPD	calculated from the maintenance rate (e.g., 5%), maintenance frequency (years), ancillary material use rate (per unit product), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) of an industry-average source
	B2.2.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), ancillary materials for repair activities, including transport and construction losses]	sim. to **A4.1.1,** based on quantities from **B2.2.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
B2.3 All processes for maintaining the functional and technical performance of the building	**B2.3.1** ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *construction-energy* (MJ, L, kWh, etc.), for maintenance activities]	sim. to **A5.1.1**			
	B2.3.2 ∑ [*water use* (m^3)] × [quantity of *construction-water* (m^3), for maintenance activities]	sim. to **A5.9.1**			
	B2.3.3 ∑ [*wastewater treatment* (m^3)] × [quantity of *construction-wastewater* (m^3), for maintenance activities]	sim. to **A5.9.2**			
B2.4 The end-of-life stage of products and of ancillary products	**B2.4.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), for maintenance activities]	sim. to **C2.1.1**, based on quantities from **B2.1.1**			
	B2.4.2 ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, for maintenance activities]	sim. to **C3.1.1**, based on quantities from **B2.1.1**			
	B2.4.3 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, for maintenance activities]	sim. to **C4.1.1**, based on quantities from **B2.1.1**			
B2.5 All cleaning processes of the interior and exterior of the building	**B2.5.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), for cleaning activities, including due to transport and construction losses]	taken (measured) from, for example, a purchase orders, purchase receipts, etc., over a period of time	estimated by project team based on project type, products used, etc.	calculated from the cleaning rate (e.g., $L/m^2/yr$), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) reported in an LCA/EPD	calculated from the cleaning rate (e.g., $L/m^2/yr$), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) of an industry-average source

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
	B2.5.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of *transport-energy* (MJ, t*km, L, etc.), for cleaning activities]	sim. to **A4.1.1**, based on quantities from **B2.5.1**			
	B2.5.3 ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *construction-energy* (MJ, L, kWh, etc.), for cleaning activities]	sim. to **A5.1.1**			
	B2.5.4 ∑ [*water use* (m^3)] × [quantity of *construction-water* (m^3), for cleaning activities]	sim. to **A5.9.1**			
	B2.5.5 ∑ [*wastewater treatment* (m^3)] × [quantity of *construction-wastewater* (m^3), for cleaning activities]	sim. to **A5.9.2**			
B3 Repair	**B3** ∑ [**B3** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
B3.1 The production and transport of the repaired part of component products, including aspects of any losses	**B3.1.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), for repair activities, including due to transport and construction losses]	taken (measured) from, for example, a purchase orders, purchase receipts, etc., over a period of time	estimated by project team based on project type, products used, etc.	calculated from the repair rate (e.g., 5%), repair frequency (years), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) reported in an LCA/EPD	calculated from the repair rate (e.g., 5%), repair frequency (years), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) of an industry-average source
	B3.1.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), for repair activities]	sim. to **A4.1.1,** based on quantities from **B3.1.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
B3.2 Production and transport of ancillary materials	**B3.2.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), ancillary materials for repair activities, including transport and construction losses]	taken (measured) from, for example, a purchase orders, purchase receipts, etc., over a period of time	estimated by project team based on project type, products used, etc.	calculated from the repair rate (e.g., 5%), repair frequency (years), ancillary material use rate (per unit product), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) reported in an LCA/EPD	calculated from the repair rate (e.g., 5%), repair frequency (years), ancillary material use rate (per unit product), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) of an industry-average source
	B3.2.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.) ancillary materials for repair activities]	sim. to **A4.1.1,** based on quantities from **B3.2.1**			
B3.3 The repair process of the repaired part	**B3.3.1** ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *construction-energy* (MJ, L, kWh, etc.), for repair activities]	sim. to **A5.1.1**			
	B3.3.2 ∑ [*water use* (m^3)] × [quantity of *construction-water* (m^3), for repair activities]	sim. to **A5.9.1**			
	B2.2.3 ∑ [*wastewater treatment* (m^3)] × [quantity of *construction-wastewater* (m^3), for repair activities]	sim. to **A5.9.2**			
B3.4 The end-of-life stage of the removed part of the component and of ancillary	**B3.4.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), for repair activities]	sim. to **C2.1.1**, based on quantities from **B3.1.1** and **B3.2.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
products, transport modes and distances for the waste	**B3.4.2** ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, for repair activities]	sim. to **C3.1.1**, based on quantities from **B3.1.1** and **B3.2.1**			
	B3.4.3 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, for repair activities]	sim. to **C4.1.1**, based on quantities from **B3.1.1** and **B3.2.1**			
B4 Replacement	**B4** ∑ [**B4** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
B4.1 Production and transport of the replaced component	**B4.1.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), for replacement activities, including due to transport and construction losses]	taken (measured) from, for example, a purchase orders, purchase receipts, etc., over a period of time	estimated by project team based on project type, products used, etc.	calculated from the replacement rate (e.g., 5%), replacement frequency (years), construction loss rate (e.g., 5%), and transport loss rate (e.g. 5%) reported in an LCA/EPD	calculated from the replacement rate (e.g., 5%), replacement frequency (years), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) of an industry-average source
	B4.1.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), for replacement activities]	sim. to **A4.1.1**, based on quantities from **B4.1.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] × [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
B4.2 Production and transport of ancillary materials	**B4.2.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), ancillary materials for replacement activities, including due to transport and construction losses]	taken (measured) from, for example, a purchase orders, purchase receipts, etc., over a period of time	estimated by project team based on project type, products used, etc.	calculated from the replacement rate (e.g., 5%), replacement frequency (years), ancillary material use rate (per unit product), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) reported in an LCA/EPD	calculated from the replacement rate (e.g., 5%), replacement frequency (years), ancillary material use rate (per unit product), construction loss rate (e.g., 5%), and transport loss rate (e.g., 5%) of an industry-average source
	B4.2.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), ancillary materials for replacement activities]	sim. to **A4.1.1**, based on quantities from **B4.2.1**			
B4.3 Replacement process of the replaced components and ancillary products	**B4.3.1** ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *construction-energy* (MJ, L, kWh, etc.), for replacement activities]	sim. to **A5.1.1**			
	B4.3.2 ∑ [*water use* (m^3)] × [quantity of *construction-water* (m^3), for replacement activities]	sim. to **A5.9.1**			
	B4.3.3 ∑ [*wastewater treatment* (m^3)] × [quantity of *construction-wastewater* (m^3), for replacement activities]	sim. to **A5.9.2**			
B4.4 End-of-life stage of the removed component and of ancillary products	**B4.4.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), for replacement activities]	sim. to **C2.1.1**, based on quantities from **B4.1.1** and **B4.2.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] × [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
	B4.4.2 ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, for replacement activities]	sim. to **C3.1.1**, based on quantities from **B4.1.1** and **B4.2.1**			
	B4.4.3 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, for replacement activities]	sim. to **C4.1.1**, based on quantities from **B4.1.1** and **B4.2.1**			
B5 Refurbishment	**B5** ∑ [**B5** (functional unit)] × [quantity of **product** (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
B5.1 Production and transport of the new building components (including production of any material lost during refurbishment)	**B5.1.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), for refurbishment activities, including due to transport and construction losses]	taken (measured) from, for example, a purchase order, purchase receipt, etc.	derived from a BIM or quantity takeoff methods, or estimated by the project team, based on a refurbishment plan, with accounting of losses	calculated from the product use rate (per unit product), construction loss rate (e.g. 5%), and transport loss rate (e.g. 5%) reported in an LCA/EPD	calculated from the product use rate (per unit product), construction loss rate (e.g. 5%), and transport loss rate (e.g. 5%) of an industry-average source
	B5.1.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), for refurbishment activities]	sim. to **A4.1.1,** based on quantities from **B5.1.1**			
B5.2 Production and transport of ancillary materials	∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), ancillary materials for refurbishment activities, including due to transport and construction losses]	sim. to **B5.1.1**			
	∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), ancillary materials for refurbishment activities]	sim. to **A4.1.1,** based on quantities from **B5.2.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
B5.3 Construction as part of the refurbishment process	**B5.3.1** ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *construction-energy* (MJ, L, kWh, etc.), for refurbishment activities]	sim. to **A5.1.1**			
	B5.3.2 ∑ [*water use* (m^3)] × [quantity of *construction-water* (m^3), for refurbishment activities]	sim. to **A5.9.1**			
	B5.3.3 ∑ [*wastewater treatment* (m^3)] × [quantity of *construction-wastewater* (m^3), for refurbishment activities]	sim. to **A5.9.2**			
B5.4 The end-of-life stage of replaced building components	**B5.4.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), for refurbishment activities]	sim. to **C2.1.1**, based on quantities from **B5.1.1** and **B5.2.1**			
	B5.4.2 ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, for refurbishment]	sim. to **C3.1.1**, based on quantities from **B5.1.1** and **B5.2.1**			
	B5.4.3 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, for refurbishment activities]	sim. to **C4.1.1**, based on quantities from **B5.1.1** and **B5.2.1**			
B6 Operational energy use	∑ [B6 (functional unit)] × [quantity of product (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
B6.1 Core building-integrated end-uses (see Section 2.3)	**B6.1.1** ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *operational-energy* (MJ, L, kWh, etc.), for use stage]	taken (measured) from, for example, a utility bill, energy meter	derived from energy simulation software or other estimation method	calculated from an LCA/EPD dataset or from the EUI of a single building (e.g. archetype, baseline, design option)	calculated from an EUI benchmark

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] × [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
B6.2 Other building-integrated end-uses (to be reported separately from B6.1).	**B6.2.1** sim. to **B6.1.1**	sim. to **B6.1.1**			
B6.3 Non-building-integrated end-uses (to be reported separately from B6.1).	**B6.3.1** sim. to **B6.1.1**	sim. to **B6.1.1**			
B7 Operational water use	∑ [B6 (functional unit)] × [quantity of product (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
B7.1 Water used and its treatment (pre- and post-use) during the normal operation of the building. Core building-integrated end-uses (see Section 2.3)	**B7.1.1** ∑ [*water use* (m^3)] × [quantity of *operational-water* (m^3), for use stage]	taken (measured) from, for example, a utility bill, water meter	derived from an estimation method	calculated from a quantity reported in an LCA/EPD or from the WUI of, for example, an archetype, existing design, design option	calculated from a WUI benchmark
	B7.1.2 ∑ [*wastewater treatment* (m^3)] × [quantity of *operational-wastewater* (m^3), for use stage]	taken (measured) from, for example, a wastewater treatment or transport bill	estimated by project team based on project information; e.g., construction equipment usage, water use, with consideration of wastewater generation rates	calculated from a quantity reported in an LCA/EPD or from the WUI of, for example, an archetype, existing design, design option, with consideration of wastewater generation rates	calculated based on a WUI benchmark, with consideration of wastewater generation rates
B7.2 Other non-building-integrated technical systems (to be reported separately from B7.1)	**B7.2.1** sim. to **B7.1.1**	sim. to **B7.1.1**			
	B7.2.2 sim. to **B7.1.2**	sim. to **B7.1.2**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
C1 Deconstruction/demolition	**C1** ∑ [**C1** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
C1.1 On-site operations and operations undertaken as necessary for the deconstruction processes after decommissioning, up to and including on-site deconstruction, dismantling and/or demolition.	**C1.1.1** ∑ [*energy use* (MJ, L, kWh, etc.)] × [quantity of *construction-energy* (MJ, L, kWh, etc.), for building deconstruction/demolition]	sim. to **A5.1.1**			
	C1.1.2 ∑ [*water use* (m^3)] × [quantity of *construction-water* (m^3), for building deconstruction/demolition]	sim. to **A5.9.1**			
	C1.1.3 ∑ [*wastewater treatment* (m^3)] × [quantity of *construction-wastewater* (m^3), for building deconstruction/demolition]	sim. to **A5.9.2**			
C1.2 Temporary works during deconstruction/demolition	**C1.2.1** ∑ [*product use* (declared unit)] × [quantity of *product* (m^3, tonnes, etc.), temporary works for building deconstruction/demolition, including due to transport and construction losses]	sim. to **A5.12.1**			
	C1.2.2 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of product *transport-energy* (MJ, t*km, L, etc.), temporary works for building deconstruction/demolition]	sim. to **A4.1.1**, based on quantities from **C1.2.1**			
	C1.2.3 ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), temporary works for building deconstruction/demolition]	sim. to **C2.1.1**, based on quantities from **C1.2.1**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
	C1.2.4 ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, temporary works for building deconstruction/demolition]	sim. to **C3.1.1**, based on quantities from **C1.2.1**			
	C1.2.5 ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, temporary works for building deconstruction/demolition]	sim. to **C4.1.1**, based on quantities from **C1.2.1**			
C2 Transport	**C2** ∑ [**C2** (functional unit)] × [Quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
C2.1 All impacts due to transportation to disposal and/or until the system boundary between product systems is reached, including transport to and from possible intermediate storage/processing locations.	**C2.1.1** ∑ [*transport* (MJ, t*km, L, etc.)] × [quantity of waste *transport-energy* (MJ, t*km, L, etc.), at building end-of-life]	taken (measured) from, for example, a fuel bill	calculated from the waste outcomes (% recycled, % reused, etc.), transport modes (truck, rail, etc.), and transport distances (km) of a project	calculated from the waste outcomes (% recycled, % reused, etc.), transport modes (truck, rail, etc.), and transport distances (km) reported in an LCA/EPD or from quantities reported in an LCA/EPD	calculated from the waste outcomes (% recycled, % reused, etc.), transport modes (truck, rail, etc.) and transport distances (km) of an industry-average source or from quantities of an industry-average source
C3 Waste processing	**C3** ∑ [**C3** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
C3.1 Collection of waste fractions from the deconstruction and waste processing of material flows intended for reuse, recycling and energy recovery.	**C3.1.1** ∑ [*waste processing* (kg)] × [quantity of *waste* (kg) to processing, at building end-of-life]	measured from, for example, a scale	calculated from the waste outcomes (% recycled, % reused, etc.) from a waste plan or those observed on site.	calculated from the waste outcomes (% recycled, % reused, etc.) reported in an LCA/EPD	calculated from the waste outcomes (% recycled, % reused, etc.) of an industry-average source
C4 Disposal	**C4** ∑ [**C4** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
C4.1 Post-transportation treatment that is necessary before disposal (neutralization, incineration with or without utilization of energy, landfilling with or without utilization of landfill gases, etc.).	**C4.1.1** ∑ [*waste disposal* (kg)] × [quantity of *waste* (kg) to disposal, at building end-of-life]	measured from, for example, a scale	calculated from the waste outcomes (%landfilled, % incinerated, etc.) from a waste plan or those observed on site.	calculated from the waste outcomes (% landfilled, % incinerated, etc.) reported in an LCA/EPD	calculated from the waste outcomes (% landfilled, % incinerated, etc.) of an industry-average source
D1 Recycling	**D1** ∑ [**D1** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
D1.1 Metals recycling	**D1.1.1** ∑ [*recycling* (kg)] × [quantity of *net output flow* (kg), of waste that is recycled] *net output flow* (kg) = ∑ [quantity of *waste* (kg), to recycling] × [(% recycled – recycled content) / % recycled] Note: *waste* (kg), to recycling comes from **A4.3.4**, **A5.10.4**, **A5.13.2**, **B2.4.2**, **B3.4.2**, **B4.4.2**, **B5.4.2**, **C1.2.4**, **C3.1.1**	calculated from measurement from, for example, a scale	calculated from the % recycled from a waste plan or those observed on site.	calculated from the recycled content (%) and % recycled (%) reported in an LCA/EPD	calculated from the recycled content (%) and % recycled (%) of an industry-average source

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] × [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
D1.2 Concrete and masonry product recycling	**D1.2.1** sim. to **D1.1.1**	sim. to **D1.1.1**			
D1.3 Bio-based products recycling	**D1.3.1** sim. to **D1.1.1**	sim. to **D1.1.1**			
D1.4 Other products recycling	**D1.4.1** sim. to **D1.1.1**	sim. to **D1.1.1**			
D2 Reuse	**D2** ∑ [**D2** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
D2.1 Reuse of products	**D2.1** ∑ [*reuse* (kg)] × [quantity of *net output flow* (kg), of waste that is reused] *net output flow* (kg) = ∑ [quantity of *waste* (kg), to reuse] × [(% reused – reused content) / % reused] Note: *waste* (kg), to reuse comes from **A4.3.4**, **A5.10.4**, **A5.13.2**, **B2.4.2**, **B3.4.2**, **B4.4.2**, **B5.4.2**, **C1.2.4**, **C3.1.1**	calculated from measurement from, for example, a scale	calculated from the % reuse from a waste plan or those observed on site.	calculated from the reused content (%), % reused (%) reported in an LCA/EPD	calculated from the reused content (%), % reused (%) of an industry-average source
D3 Energy recovery	**D3** ∑ [**D3** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			

Information module or activity	Equation: Environmental indicator result = ∑ [environmental data] **×** [flow quantity] See Table 8 for environmental data types and Table 6 for flow types	Bill of flows quantity derivation			
		Primary	Project-specific	Product-specific	Secondary
D3.1 Energy recovery of products	**D3.1.1** ∑ [*energy recovery* (kg)] × [quantity of *net output flow* (kg), waste for energy recovery] *net output flow* (kg) = ∑ [quantity of *waste* (kg), to energy recovery] Note: *waste* (kg), to energy recovery comes from **A4.3.4**, **A5.10.4**, **A5.13.2**, **B2.4.2**, **B3.4.2**, **B4.4.2**, **B5.4.2**, **C1.2.4**, **C3.1.1**	sim. to C3.1.1			
D4 Exported energy	**D4** ∑ [**D4** (functional unit)] × [quantity of *product* (m^3, tonnes, etc.), for initial construction]	sim. to **A1-A3**			
D4.1 Exported energy during building operation	D4.1.1 ∑ [*exported energy* (MJ))] × [quantity of *exported energy* (MJ), during operation] Note: see Annex B of EN 15978 for case study examples of how to treat exported energy	sim. to B7.1 Note: see Annex B of EN 15978 for case study examples of how to treat exported energy			

Appendix D – Environmental indicators

Table 11: Environmental indicators per EN 15978:2011

Environmental indicator	Unit
Indicators describing environmental impacts (default TRACI 2.1 units shown)	
Global warming potential	kg CO_2 eq.
Depletion of the stratospheric ozone layer	kg CFC-11 eq.
Acidification potential of land and water	kg N eq.
Eutrophication potential	kg SO_2 eq.
Formation potential of tropospheric ozone photochemical oxidants	kg O_3 eq.
Indicators describing resource use	
Renewable primary energy excluding energy resources used as raw material	MJ, NCV
Renewable primary energy resources used as raw material	MJ, NCV
Non-renewable primary energy excluding resources used as raw material	MJ, NCV
Non-renewable primary energy resources used as raw material	MJ, NCV
Secondary material	kg
Renewable secondary fuels	MJ, NCV
Non-renewable secondary fuels	MJ, NCV
Net use of fresh water	MJ, NCV
Indicators describing waste categories	
Non-hazardous waste disposed	kg
Hazardous waste disposed	kg
Radioactive waste disposed	kg
Indicators describing the output flows leaving the system	
Components for reuse	kg
Materials for recycling	kg
Materials for energy recovery (not being waste incineration)	kg
Exported energy	kg

Table 12: Environmental indicators per ISO 21930:2017

Environmental indicator	Unit
Environmental impacts (default TRACI 2.1 units shown)	
Global warming potential	kg CO_2 eq.
Ozone depletion potential	kg CFC-11 eq.
Eutrophication potential	kg N eq.
Acidification potential	kg SO_2 eq.
Photochemical oxidant creation potential	kg O_3 eq.
Use of primary resources	
Renewable primary resources used as an energy carrier (fuel)	MJ, NCV
Renewable primary resources with energy content used as material	MJ, NCV
Non-renewable primary resources used as an energy carrier (fuel)	MJ, NCV
Non-renewable primary resources with energy content used as material	MJ, NCV
Use of secondary resources	
Secondary materials	kg
Renewable secondary fuels	MJ, NCV
Non-renewable secondary fuels	MJ, NCV
Recovered energy	MJ, NCV
Abiotic depletion potential for fossil resources	
Abiotic depletion potential for fossil mineral resources	MJ, NCV
Consumption of freshwater resources	
Consumption (or net use) of freshwater	m^3
Waste and output flows	
Hazardous waste disposed	kg
Non-hazardous waste disposed	kg
High-level radioactive waste, to final repository	kg or m^3
Intermediate- and low-level radioactive waste, to final repository	kg or m^3
Components for reuse	kg
Materials for recycling	kg
Materials for energy recovery	kg
Recovered energy exported from the product system	kg
Additional inventory parameters for transparency	
Removals and emissions associated with biogenic carbon content of the bio-based product	kg CO_2 eq.
Emissions from calcination and removals from carbonation	kg CO_2 eq.
Removals and emissions associated with biogenic carbon content of the bio-based packaging	kg CO_2 eq.
Emissions from combustion of waste from renewable sources used in production processes	kg CO_2 eq.
Emissions from combustion of waste from non-renewable sources used in production processes	kg CO_2 eq.

Appendix E – Carbonation

This information is from EN 16757:2017 Annex BB.

Table 13: k-factors and degrees of carbonation for concrete

Exposure	k-factor by concrete strength, in mm/year$^{0.5}$				Degree of carbonation, Dc
	< 15 MPa	15 to 20 MPa	25 to 35 MPa	> 35 MPa	
Outdoor					
Exposed to rain	5.5	2.7	1.6	1.1	0.85
Sheltered from rain	11	6.6	4.4	2.7	0.75
Indoor dry climate[c]					
With cover[b]	11.6	6.9	4.6	2.7	0.40
Without cover	16.5	9.9	6.6	3.8	0.40
In ground[a]					
In ground		1.1	0.8	0.5	0.85

[a] Under groundwater level, k = 0.2

[b] Paint or wallpaper; under tiles, parquet and laminate k is considered to be 0.

[c] Indoor dry climate means that the RH is normally between 45% and 65%.

Table 14: s-factor corrections for cement or concrete with additional mineral components

Type of mineral	Amount of additional weight (weight %)					
	< 10	10 to 20	20 to 30	30 to 40	40 to 60	60 to 80
Limestone		1.05	1.1			
Silica fume	1.05	1.10				
Fly ash		1.05			1.10	
GGBFS	1.05	1.10	1.15		1.2	1.3

Appendix F – Additional resources

Additional guidance

Carbon Leadership Forum (2019). *Life Cycle Assessment of Buildings: A Practice Guide, v1.1*. http://www.carbonleadershipforum.org/projects/lca-practice-guide/

- Provides an introduction to the background and methodology of wbLCA and high-level guidance on practice.

International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Annex 57 (2016). *Guideline for Designers and Consultants – Part 1: Basics for the Assessment of Embodied Energy and Embodied GHG Emissions for Building Construction.*

- The section titled "Integration of embodied impacts assessment into the design process" provides guidance on how wbLCA practitioners can influence the embodied impacts of a project according to the stage of the design, and the main design tasks and embodied impacts checkpoints during the design and tendering process.

International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Annex 57 (2016). *Guideline for Designers and Consultants – Part 2: Strategies for Reducing Embodied Energy and Embodied GHG Emissions*.

- Provides guidance on impact reduction strategies during design. Covers product substitutions, reduction of resource use, and reduction of construction and end-of-life stage impacts.

American Society of Civil Engineers (ASCE)/Structural Engineers Institute Sustainability Committee, (2017). *Guide to Definition of the Reference Building Structure and Strategies in Whole Building Life Cycle Assessment*.

- Part II of this guide describes design strategies that structural engineers might use to reduce environmental impact.

Common reference unit calculation methods

Gross floor areas

- The Canadian Institute of Quantity Surveyors (CIQS) (2006) *Elemental Cost Analysis Measurement of Buildings by Area and Volume* (available for purchase) outlines a calculation method for external gross area. The method is described in Appendix A.

- The Building Owners and Managers Association International (BOMA International) has a series of standards[26] for calculating gross external and gross internal floor areas:
- Office Buildings: Standard Methods of Measurement (ANSI/BOMA Z65.1 – 2010).
- Industrial Buildings: Standard Methods of Measurement (ANSI/BOMA Z65.2 – 2012).
- Gross Areas of a Building: Standard Methods of Measurement (ANSI/BOMA Z65.3 – 2009).
- Multi-Unit Residential Buildings: Standard Methods of Measurement (ANSI/BOMA Z65.4 – 2010).
- Retail Buildings: Standard Methods of Measurement (ANSI/BOMA Z65.5 – 2010).
- Mixed-Use Properties: Standard Methods of Measurement (ANSI/BOMA Z65.6 – 2012).
- The International Property Measurement Standards (IPMS) has a series of free internationally recognized calculation standards[27] for offices (2014), residential (2016), industrial (2018), and retail buildings (2019), with standards for schools, hospitals, hotels and student accommodation expected in the future. Each volume has three methods:
  1. IPMS-1: an external gross area calculation that is used for planning purposes or costing of development proposals. This method is the same across each building type,
  2. IPMS-2: internal gross area methods which provide data on the use of space and for benchmarking; different components may be reported separately, and
  3. IPMS-3: is for measuring the floor areas of exclusive use and therefore is more useful as a method to differentiate between spaces than as a reference unit for wbLCA.

Net floor areas

- The BOMA International standards noted above include some net floor area calculation methods; e.g., rentable area.

Number of occupants

- Table 3.1.17.1. of the National Building Code of Canada 2015 (NBC) provides occupant design loads for various building functions.
- Table 1004.1.2 of the International Building Code (IBC) provides occupant design loads for various building functions.
- ASHRAE 62.1 Table 6-1 provides occupant design loads for various building functions, based on ventilation needs.
- LEED® Reference Guides outline the methodology for calculating a building's full-time equivalent. See http://succeedatleed.com/make-calculating-ftes-less-confusing/ for more information.

[26] Available for purchase at https://www.techstreet.com/boma/subgroups/55842

[27] https://ipmsc.org/standards/

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