Report

Applying Circularity in the Life Cycle Assessment of Buildings

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Le lab construction est un projet du Centre d'études et de recherches intersectorielles en économie circulaire de l'ÉTS (CERIEC).

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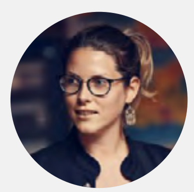

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About CERIEC-ÉTS

Established in September 2020, CERIEC's mission is to contribute to the shaping and deployment of circular economy through a program of cutting-edge interdisciplinary scientific research and through training, dialogue, valorization and transfer initiatives designed to maximize benefits for economic actors, governments and civil society.

CERIEC intends to become the inescapable reference in terms of knowledge, skills, and value creation around circular economy in Québec.

Located at ÉTS (École de Technologie Supérieure), it provides an important space for researchers and students for experimentation, particularly in the area of innovations designed to facilitate the transition to a sustainable future.

About CERIEC's construction lab

The Circular Economy Acceleration Lab (Construction lab) aims to demonstrate ways to integrate and generalize circular economy strategies in the construction sector through innovative experimentation projects co-created with stakeholders.

The acceleration lab is inspired by the concept and practices of living labs, which apply to projects that require the involvement of users, experimentation in real contexts and multi-stakeholder collaboration. The lab's collaborative method makes it possible to implement innovations quickly, test what works and facilitate the appropriation of new practices.

About this report

This report is the deliverable of the co-created project: Applying Circularity in the Life Cycle Assessment of Buildings, led by Arup and ÉTS in collaboration with Groupe AGÉCO and Studio Carbone. It is one of the many projects of the First Living Lab on Circular Economy in the Construction Sector spearheaded by the CERIEC. The lab's initiative is to provide solutions to identified challenges to implement circular economy in Québec's construction industry.

Contents

Glossary

Benefit
In the context of a life cycle assessment, a benefit is the reduction in impact brought on by a design or construction strategy, relative to a reference system where that strategy was not implemented.

Biogenic carbon
All the carbon that is sequestered from the atmosphere during the growth of trees, plants, and other biomass. Biogenic carbon emissions represent the carbon dioxide or methane released during combustion or decomposition of materials containing biogenic carbon.

Burden
Burden is synonymous with life cycle impact for this report.

Carbon storage
Temporary or permanent storage of carbon after it has been sequestered from the atmosphere.

Circular strategies
In this report, circular strategies represent all potential approaches to building design and construction which improve the material sustainability of a building (and circularity), either through reducing the demand for primary materials, or by moving demand to less impactful primary materials.

Circularity
The term circularity, and by extension circular economy, is generally used to describe the concept of achieving sustainability through material reuse and material efficiency.

Design for adaptability (DfA)
Designing buildings such that they can be modified in response to changes in needs and circumstances, thus keeping the building useful for longer periods of time.

Design for deconstruction (DfD)
Also known as design for disassembly, it refers to design decisions that will encourage, both economically and in practice, the easy dismantling of a building to favor the recovery and reuse of its components.

End-of-life
The last life cycle stage of a building or component, equivalent to life cycle stage C. It consists of all the activities taking place between the beginning of demolition or deconstruction and the end-of-waste state for all materials. This is not to be confused with the end-of-life formula from the PEF Guideline.

End-of-waste state
The boundary condition at the end of a building system, as defined by EN 15978. When materials reach this state at the end of the processes making up life cycle stage C, they leave the system. In addition, any further environmental impacts associated with the materials are not attributed to the original building system. Materials may leave the system in several ways: as waste, as an input to an energy recovery process, and as an input to recycling processes for which impacts are attributed to a new building system.

Environmental product declaration (EPD)
A standardized document communicating the life cycle impacts of a product, process, or services, calculated using the appropriate Product Category Rules (PCR). EPDs are a type 3 environmental declaration according to ISO 14025 and are defined using life cycle assessment tools.

Functional equivalence
A property of two buildings, typically a project building and a reference building, which meet the same functional and/or technical requirements. These requirements can include service life, performance standards, and patterns of use. For a detailed definition of functional equivalence see the ASCE guide for the definition of the reference building structure and strategies in whole building life cycle assessment.

Functional unit
Defined by ISO 14040/44 as the quantified performance of a product system for use as a reference unit. This represents a normalizing unit of environmental emissions and impacts comparison across multiple projects and/or reference systems. The functional unit in a whole building life cycle assessment can be the total impacts of building itself or a subset of it, such as impacts per square meter of gross floor area or impact per residential unit.

Global warming potential (GWP)
A relative measurement that allows the impacts of different greenhouse gases to be compared to one another, given their different abilities to absorb energy and differing lifetimes. GWP is measured relative to carbon dioxide (CO_2), which has a GWP of 1, while other gases have a multiplier representing their relative warming impact per kg over a specified time period, which is typically 100 years.

Life cycle assessment (LCA)
A method for assessing the environmental impacts associated with a product, process, or service. These impacts may be calculated for all life cycle stages (A, B, C) through disposal or recycling. LCAs of complicated products typically involve combining the results of LCAs for individual components.

Life cycle impact
Any type of environmental impact during the whole life cycle (i.e., from material extraction to end-of-life) that can be quantified according to impact category indicators. Impacts are often defined via a characterization process, which converts individual environmental inflows (freshwater use, resource depletion) or outflows (GHG emissions) from a life cycle inventory into a common midpoint or endpoint unit of comparison.

Life cycle inventory (LCI)
The inventory contains data used as input to a life cycle assessment that quantifies the material flows, energy flows, and environmental impacts of any given product, service, or process.

Lifespan/service life
The period of time that a building or component is in use before its end-of-life or replacement. The lifespan of a building depends on various factors, such as maintenance, materials used, weather and climate conditions, design decisions, etc.

Recovery rate (RR)
The proportion of a material or group of materials which is recovered for reuse at the end-of-life.

Reference building/system/scenario
A building against which the environmental impacts of a proposed building are compared. The reference building typically represents a business-as-usual scenario and may be based on existing buildings, building archetypes, or an earlier design stage of the same building.

Secondary materials
All materials and products that have already fulfilled their primary intended use. This includes both recycled material and material that is destined to be recycled.

Whole building life cycle assessment (WBLCA)
An evaluation of the environmental impacts of a whole building throughout its life cycle stages. It includes embodied and operational emissions.

Standards and Guidelines

The following table summarises the standards and guidelines referenced in this document. These govern the guiding principles and requirements for conventional life cycle assessments (LCAs) and whole building life cycle assessments (WBLCAs).

Table 1. Summary of standards and guidelines for LCA and WBLCA

Code: Date	Title	Topic	Description
Standards and guidelines on LCA in construction			
2022	National guidelines for whole-building life cycle assessment (referred to as the National Guidelines in this report)	WBLCA general principles	The guidelines provide instructions to harmonize the practice of LCA as applied to Canadian buildings, based on relevant standards and their intentions. It primarily references EN 15978 and ISO 21930, but also ISO 14044 and ISO 21678.
EN 15978: 2011	Sustainability of construction works - Assessment of environmental performance of buildings- Calculation method	WBLCA rules and methods	This standard describes the assessment method of environmental performance at the building level. Product-level impacts are governed by EN 15804. Canadian guidelines are primarily keyed to this norm. Although it is a European standard, it is increasingly the reference for WBLCA along with EN 15804.
EN 15804: 2012 + A2:2019	Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products	Rules for EPDs of construction products	It presents the methodology for generating harmonized EPDs at the level of construction products (feeds into EN 15978 which operates at the building level). The 2019 update is no longer compliant with ISO 21930 as it covers biogenic carbon and requires declaration of an end-of-life scenario and assessment of Module D.
ISO 21930: 2017	Sustainability in buildings and civil engineering works - Core rules for environmental product declarations of construction products and services	Rules covering both WBLCA and LCA of construction products	This ISO standard combines product (EPD) and building-level guidelines. The 2017 update adopts and elaborates on many elements from EN 15804 but is not compliant with its 2019 update. It contains guidelines for biogenic carbon and concrete carbonation which are not present in EN 15978 (but have been included in EN 15804 update). It complements ISO 14025, which guides EPDs more generally. This document is more commonly used outside of Europe.
2017	ASCE - Guide to the definition of the reference building structure and strategies in whole building life cycle assessment (referred to the ASCE guide in this report)	Defining reference structure for WBLCA	This guide is from the American Society of Civil Engineers on how to define a reference structure to compare the WBLCA performance of a project. This document outlines strategies for reducing life cycle impacts on projects and considerations for defining a reference structure in those instances.

Code: Date	Title	Topic	Description
General standards on LCA			
ISO 14040: 2006	Environmental management - Life cycle assessment - Principles and framework	General LCA methodology	It presents the general principles and framework for an LCA.
ISO 14044: 2006	Environmental management - Life cycle assessment - Requirements and guidelines	General LCA methodology	This standard is complimentary to ISO 14044 but sets out specific requirements and guidelines.
PEF 2018	Product Environmental Footprint Category - Rules Guidance	Rules for PEFs of products	PEFs are an alternative to EPDs but focus on many different product categories instead of just construction. It was developed by the European Commission.
Standards on carbon accounting			
ISO 14067: 2018	Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification	LCA - GHGs	This document standardizes quantification and reporting processes for embodied carbon. It specifies that biogenic and non-biogenic emissions should be separated.
PAS 2050:2011	Specification for the assessment of the life cycle greenhouse gas emission of goods and services	GHG accounting principles	These are more general guidelines for accounting embodied GHG emissions in goods and services. It is the first product-level carbon footprint accounting protocol.
General guidelines on sustainability in the built environment			
PAS 2080:2023	Carbon management in buildings and infrastructure	Guidelines for decarbonizing built environment	It is a global standard for managing carbon in the built environment. It sets out how to quantify carbon and outlines strategies for decarbonization. The latest changes ensure consistency with EN 15978 and EN 15804.
ISO 21678:2020	Sustainability in buildings and civil engineering works - Indicators and benchmarks - Principles, requirements and guidelines	Sustainability in the built environment	The standard covers principles and guidelines for assessing social, economic, and environmental performance using benchmarks and indicators.

Note: For readability, only the code or a shortened title will be referenced across the report.

Introduction

Objective

This report outlines how the introduction of circular design and construction strategies can influence the practice of Whole Building Life Cycle Assessments (WBLCA).

Circular strategies are gaining momentum as a solution to meet sustainability targets and represent a departure from the conventional linear approach to building design and construction. Determining the impacts of buildings featuring these strategies thus requires the adjustment of standard approaches to WBLCA. This report is intended to help WBLCA practitioners in modelling and accounting for circular strategies. It thus begins with an overview of circular strategies and and an overview of WBLCA practices, as well as a detailed explanation of the necessary considerations when studying the environmental impacts of buildings which integrate circularity. It can be used to inform both the process of straightforward impact accounting and the process of scenario-design for decision-making purposes at the design stage. The goal of the report is not to re-define circular economy or WBLCA principles, only to summarize and describe how they can be best applied in practice and accounted for based on current standards, guidelines, and research.

Context

This report primarily references the National Guidelines, which outline how life cycle assessments (LCA) of Canadian buildings must be conducted. The National Guidelines and this report both reference relevent ISO and EN standards for WBLCA and LCA methodologies. In instances where topics are not covered by existing standards and guidelines, or when there is a lack of consensus, additional information is supplied from academic research. This report considers that readers have general knowledge regarding WBLCA and circular economy.

Although the practice of WBLCA in Canada is closely tied to software tools that make use of proprietary data and follow established standards, this report does not provide "Step by step" guidelines for the assessment of circular strategies with such tools. This is beyond the scope of this report. The document *Comparatif des outils d'ACV* by Studio Carbone provides an overview of the current state of WBLCA tools in Canada and their challenges to integrate circularity.

Structure

This report is structured into two parts:

Part A contains an overview of circular strategies in construction, WBLCA practices, as well as an outline of the challenges faced when performing a WBLCA with circular strategies and when defining a reference scenario.

Part B is broken up into seven chapters, each representing a circular strategy or group of strategies. Each chapter goes over the following topics: how this strategy influences life cycle impacts, how to model this strategy and how to perform a comparison with a reference system.

Part A -
Overview of Circular Strategies and WBLCA

Part A contents:

Circular Strategies

This report addresses the following circular strategies, organized in three overarching categories.

B1. Strategies that share materials across systems
- B1.1 Use of recycled materials and reused components
- B1.2 Design for deconstruction
- B1.3 Renovation of existing buildings

B2. Strategies that increase building utilization
- B2.1 Design for longevity
- B2.2 Design for spatial intensification

B3. Strategies that reduce material impacts
- B3.1 Material sobriety and material selection
- B3.2 Use of materials that store biogenic carbon

There are many ways to define circular strategies and implement circularity in the construction sector. However, their impact quantification using WBLCA or other methods remains a challenge. The application of circularity to the built environment is well described in the framework of the Circular Buildings Toolkit developed by Arup and the Ellen MacArthur Foundation. The publicly available toolkit provides a comprehensive list of circular economy principles and a prioritised set of strategies and actions that can be applied to real-estate projects. The four principles are:

1. Build nothing
2. Build for long term value
3. Build efficiently
4. Build with the right materials

These principles are operationalized by strategies:

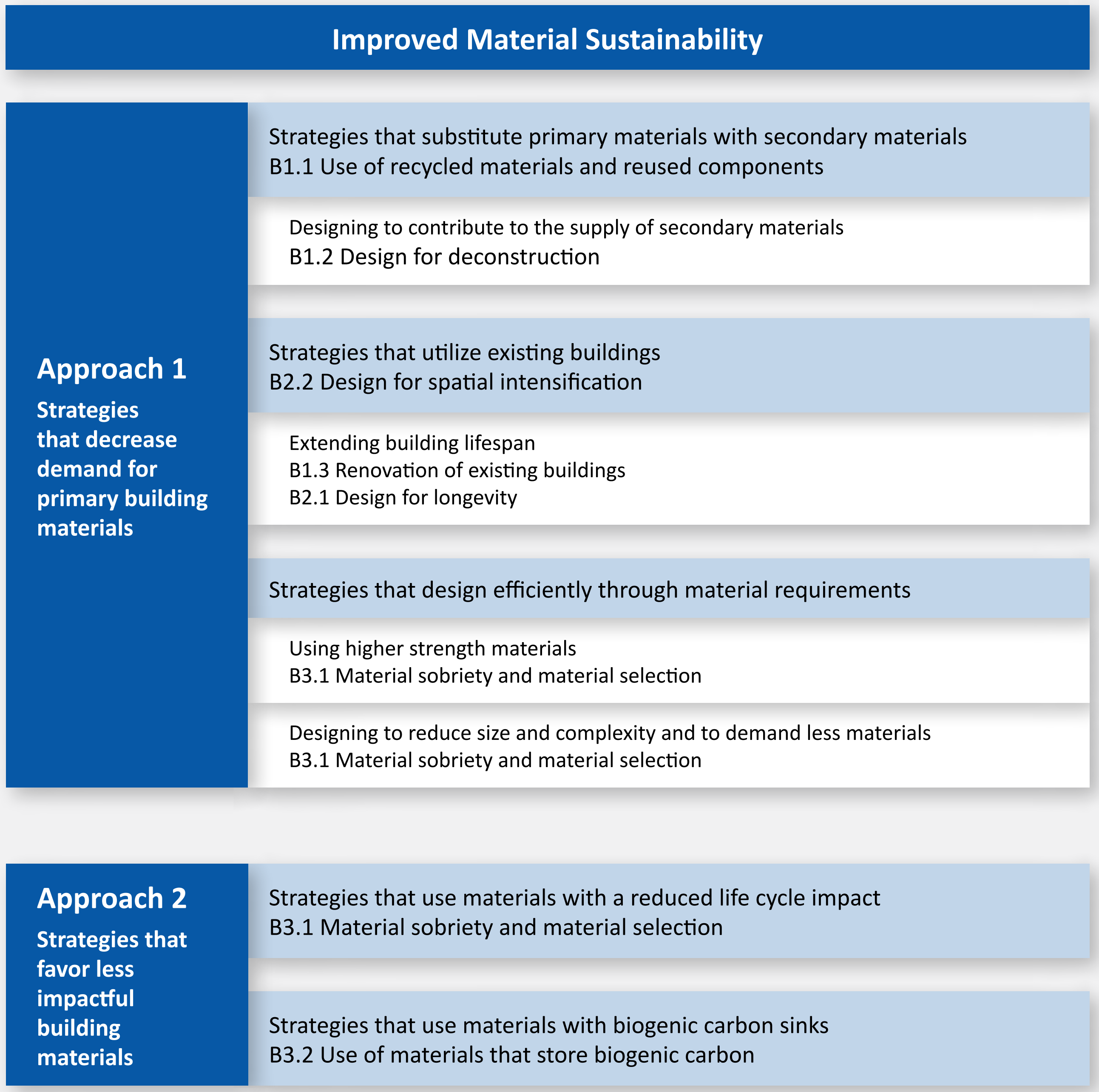
- Refuse unnecessary new construction or components
- Increase building utilization and material efficiency
- Design for longevity/adaptability/disassembly
- Reduce the use of virgin
- Non-renewable, and carbon-intensive materials
- Design out hazardous materials

The strategies themselves are implemented as a collection of actions during the project stage. Examples of actions include reversible connections, reducing finishes, avoiding basement construction, increasing convertibility, products-as-a-service, flexible walls, high-strength materials, material passports, etc.

Despite providing a thorough tool to define circularity in the built environment, the categorization of strategies provided by the Circular Buildings Toolkit is not perfectly aligned with the outcome-oriented nature of WBLCA methodology. Outcomes are the reductions or increases in building lifecycle impacts which result from the implementation of circularity strategies and actions. The actions and strategies as defined by the toolkit feature significant overlap in outcomes, while WBLCA modeling requires these outcomes to be assessed individually. A single strategy or action can result in multiple outcomes which should be modelled separately. For example, modular design principles introduce material efficiencies, reduce construction impacts, and facilitate the future deconstruction of the building system. Conversely, different strategies or actions can represent different ways to obtain the same outcome. For example, material sobriety, engineered-wood products, and low carbon steel all reduce primary material production impacts. For the reasons outlined above, this report defines a 'circular strategy' as representing all approaches to building design and construction which reduce impacts in a certain way (see Figure 1).

In practice, this report characterizes circular strategies by their outcomes (or their direct impact on how the WBLCA is conducted), rather than by their design approach (which is done in the Circular Buildings Toolkit). In Part B, each chapter represents a grouping of strategies which share a common outcome, and therefore requires similar WBLCA modelling approaches. The chapters explain how to adapt a WBLCA to account for the sought goal of a circular strategy.

Figure 1: Summary of possible improved approaches to material sustainability



Challenges with introducing circular strategies to traditional WBLCA

The growing interest in circularity in construction is presenting new challenges to the practice of WBLCA. The module-based WBLCA (Figure 2), as defined by both ISO and EN standards, is divided into distinct life cycle stages to effectively quantify the environmental impacts associated with different project stages. The conventional approaches to WBLCA were conceived for linear closed-end projects with clearly defined material lifespans and system boundaries, and as such can be ill-suited to projects with a significant circularity component.

This linear approach does not properly capture reductions in environmental impacts or benefits which are caused by circular strategies, and which often take place beyond the building's own system boundary.

Examples of benefits which exist outside the system boundary include those from design for deconstruction (DfD), which facilitates the reuse of secondary materials in future construction projects, and renovation and design for adaptability strategies, which displace the need for future construction by lengthening the operational lifespan of existing buildings. Conventional approaches to WBLCA are difficult to apply in projects where building system boundaries are blended and where materials and components are shared between projects through deconstruction and reuse. This is especially the case for renovations, where the entire building can be conceptualized as a reused component.

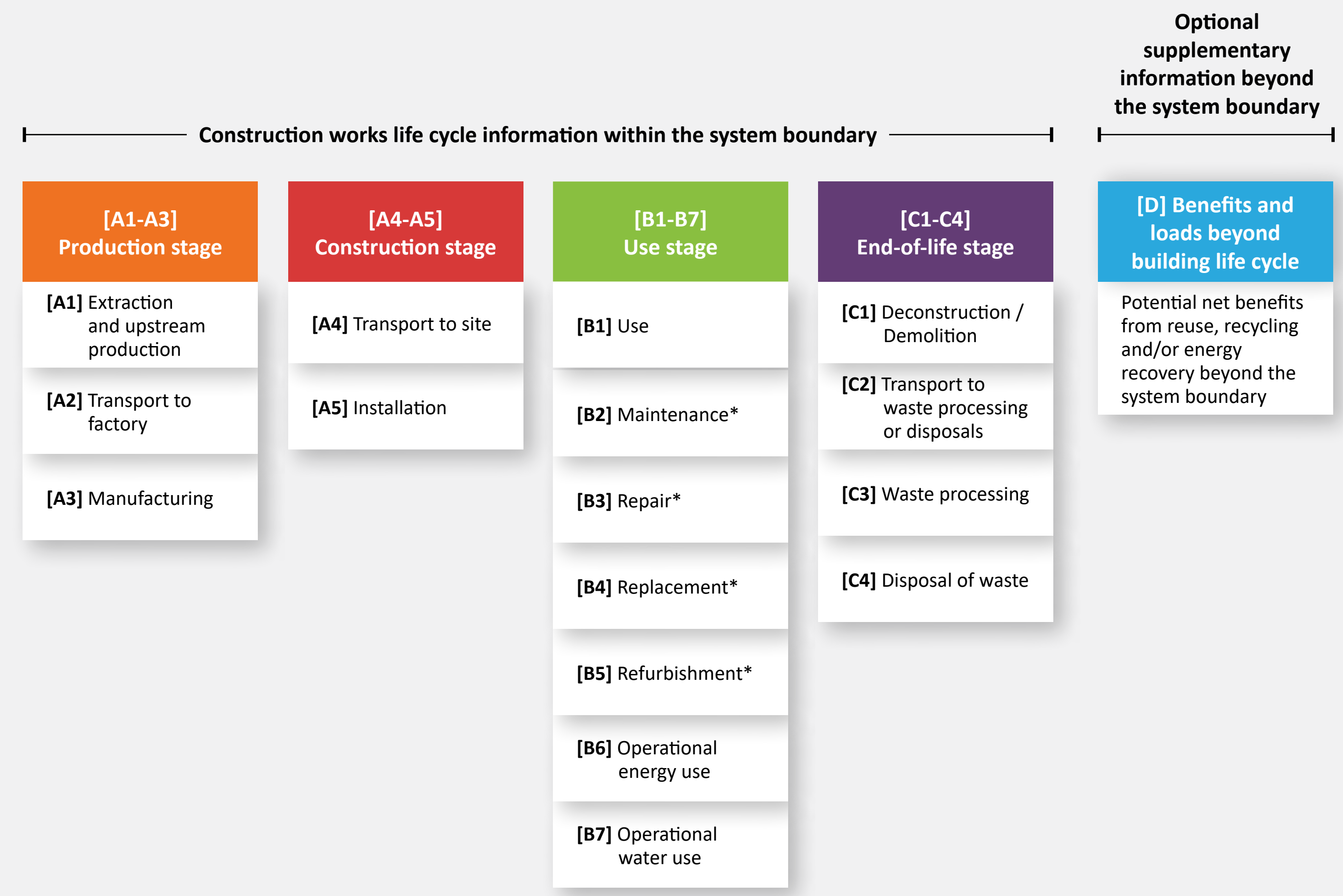
It is a challenge for practitioners to know how to allocate impacts across building systems, especially with current gaps and diverging guidance in WBLCA and LCA standards.

Module D: Why is it relevant to circularity?

Module D plays an important role in capturing the benefits of circular strategies, many benefits are derived from outcomes taking place outside of the system boundary.

Module D is in the fourth life cycle stage that is defined in ISO 21930 (7.1.7.6) and EN 15978 (7.4.6) with the purpose of capturing loads and benefits which exist outside the system boundary. Both standards specify that Module D results should be kept distinct from the results of life cycle stages A-C. This module is not considered an explicit life cycle stage and is often used to account for circularity concepts. In addition, assumptions behind the calculations should reflect current practices and technologies. Nevertheless, there remains an ambiguity as the standards only discuss reuse, recycling, and energy recovery, while there exist several other types of benefits which may take place outside the system boundary. Again, these can include the benefits of renovations and adaptation, which displace the need for future construction, and the benefits arising from biogenic carbon storage. The latter is already included in Module D in certain frameworks and tools, such as the Athena Impact Estimator for Buildings. Many standards provide guidelines for biogenic carbon accounting, though they are not well-aligned.

Figure 2: Stages and Modules of the WBLCA according to ISO 21930:2017(E)



Including production, transport and disposal of necessary materials

Defining a reference building for WBLCA

The definition of a reference building is essential for quantifying the benefits and burdens of implementing circular strategies compared to conventional construction practices.

- The National Guidelines include a section on benchmarking, which involves the definition of a reference point (or benchmark) against which a building can be compared to. The guidelines do not cover the definition of reference buildings, and they refer to the ASCE guide that outlines the assumptions to be included in the definition of a realistic reference building.
- The ASCE guide built upon the Athena Guide to Whole-Building LCA in Green Building Programs, Appendix B: FURTHER RECOMMENDATIONS FOR THE REFERENCE BUILDING DESIGN but simplified the options from 4 to 3.
- ISO 21678 provides a framework for identifying benchmarks including the sources of information that might be used, which includes surveys, statistics, as well as reference buildings.
- Environmental certifications and standards, such as LEED and CaGBC's Zero Carbon Building (ZCB), also provide some instructions to define a building baseline for WBLCA comparison to meet required credits and targets.

A reference building usually represents the business-as-usual (BAU) approach to constructing a building which satisfies the same set of functional requirements as the project building. It may be based on an analysis of representative existing buildings, the state of conventional practices, or an earlier version of the design. This raises the issue that as environmental design strategies become commonly adopted across the industry, the definition of the reference building will also change over time.

The ASCE guide is strict in its definition of the reference building, advising that the reference building should be functionally equivalent to the project building and identical in all ways except for the materials or components being changed.

This strict approach has limitations when circular strategies lead to buildings which feature different programs and/or structural systems from what would have been built under BAU. In these instances, a realistic reference building would no longer be functionally equivalent to the proposed design. The ASCE guide recognizes this and states that deviations from the strict definition of functional equivalence may be acceptable in instances where alternative structural systems are being proposed as it is "in line with the spirit and intent of LCA, which was created to aid in the improvement of product designs and processes". The ASCE guide should therefore be followed in straightforward cases where materials and components are substituted within a relatively static design.

In cases where strategies result in significant changes to the structural system, increased building lifespan, or (minor) differences in functionality, then deviations between the project and its reference buildings may be appropriate and remain aligned with the intent of the ASCE guide. These cases are identified in the individual chapters in Part B of this report. In these instances, it is crucial for the reference building to accurately represent the type of building that would otherwise have been built under BAU, and all assumptions should be clearly documented. Finally, when multiple different strategies are being compared to one another, the reference building serves as the common denominator between them, with a clearly specified function and lifespan. Table 2 presents relevant reference building systems to each circular strategy. These are further examined in Part B.

Table 2. Circular strategies and reference buildings for comparison

Circular strategy	Outcome of the strategy	Reference building system
B1. Strategies that share materials across systems		
B1.1 Use of recycled materials and reused components	Building built with lower impact materials as their impact is allocated to previous system.	Identical building but built with conventional materials.
B1.2 Design for deconstruction	Building whose materials will be reused or recycled in the future at an increased rate.	Identical building whose materials are recycled and reused at conventional rates.
B1.3 Renovation of existing buildings	Extension to building life or creation of a new building system using the previous structure as a reused component.	Depending on how the renovation system is defined: multiple buildings on the same site, demolition and reconstruction of a new building, other approaches.
B2. Strategies that increase building utilization		
B2.1 Design for longevity	Building with design approaches such as design for adaptability that increase the anticipated building lifespan.	Single building with conventional lifespan assessed using a new time-based functional unit (impact/year). Alternatively, multiple buildings designed for different uses with conventional lifespans built sequentially on the same site, or single building with expanded maintenance needs and increased replacement of its components to accommodate the change in use.
B2.2 Design for spatial intensification	Building with design approaches that increase the density of activity in the present.	Single building with conventional density of activity assessed using a new activity-based functional unit (impact/m², impact/unit, impact/occupant). Alternatively, multiple buildings with conventional design built in parallel.
B3. Strategies that reduce material impacts		
B3.1 Material sobriety (and material selection)	Building designed with greater material efficiency and other design changes (ex: void form slabs, cellular beams, eliminating finishes).	Building with conventional design and building system.
B3.1 (Material sobriety and) material selection	Building built with low impact (ex: low-carbon) materials.	Identical building but built with conventional materials.
B3.2 Use of materials that store biogenic carbon	Building with a bio-based building system, or which uses engineered, bio-based components.	Building with conventional non-carbon-storing building systems.

Considerations for a circular WBLCA

There are some general reflections and decisions that should be considered when undertaking a WBLCA that aims to account for circular strategies, such as:

Goal of the WbLCA

At what design stage is the WBLCA being conducted?

If it is being conducted during the concept design stage as an aid to decision-making, the analysis will require less detailed design inputs but instead a larger focus on multiple alternative scenarios. If it is being conducted to determine the overall impact of a finalized design (possibly as part of an environmental certification process), then a higher level of detail is required.

System boundary

What processes are being included as part of the system being studied?

Specific stages or modules may be mandatory or optional depending on the certification scheme being pursued or the governing norms, with newer European norms making Stages C and D mandatory in addition to Stages A and B. Analyses of renovations may include the demolition or deconstruction of existing buildings, or alternatively only focus on the new materials being introduced.

Project lifespan

What is the anticipated project lifespan?

If the anticipated project lifespan is longer than comparable buildings and/or the reference period set out by standards guiding WBLCA, then performing an effective comparison will require one of the following: 1) pro-rating the use-phase of one of the projects such that their lifespans match, or 2) employing a time-based functional unit such as impact/year as a basis of comparison. If the project lifespan becomes longer than the lifespan of any materials or components, then additional replacement impacts should be factored in.

Reference building

Is a reference building necessary and how is it being defined?

A reference building may be based on an analysis of existing buildings, conventional practices, or an earlier version of the design. Once it has been defined, what is the functional unit used for comparison? The functional unit may represent the entire building or a normalized unit such as square meter of gross floor area.

Overview of how to model circular strategies in WBLCA

Table 3. Circular strategies and reference buildings for comparison

Strategy Name	Definition	Benefit INSIDE or OUTSIDE system	Mechanism of the benefit	How to model in WBLCA	Additional life cycle impacts to consider
B1. Strategies that share materials across systems					
B1.1 Use of recycled materials and reused components	Use of recycled materials and reused components.	INSIDE: Reduction of burdens in Stage A. Most reduction is typically in Module A1.	Reduces the demand for virgin materials and their associated impacts, while the impacts of secondary materials are allocated to their previous system.	This requires an analysis of impacts associated with reuse and recycling processes. Adjustments may be necessary to account for material degradation.	New impacts associated with recycling processes and transportation.
B1.2 Design for deconstruction	Design strategies which facilitate the deconstruction, rather than demolition, of a building.	INSIDE: Change in burdens in Stage C.	Facilitates the reuse of materials and components by future projects. Allows future projects to avoid life cycle impacts associated with production of virgin materials.	Avoided production impacts in future projects are calculated as in B1.1 but are accounted in the Module D of the project in question.	Deconstruction is typically more energy intensive than standard demolition.
B1.3 Renovation of existing buildings	Reuse of an existing building and its components.	OUTSIDE: Benefit measured relative to reference scenario equivalent to a new building built on site.	Avoids the impacts associated with a new cycle of construction and demolition.	Renovations can be treated as use-stage processes of an existing system, or the beginning of a new system in which the existing structure is treated like a reused component. There are multiple possible approaches to comparing renovation and new-build scenarios.	Complex renovations may be more energy intensive than new construction. Use-stage impacts may be higher than new construction.
B2. Strategies that increase building utilization					
B2.1 Design for longevity	Design strategies to increase anticipated building lifespan.	OUTSIDE: Benefit measured relative to reference scenario equivalent to a new building built on site.	Reduces need for future construction and spreads the impacts of construction and demolition over a longer period of time.	LCA is conducted in typical manner. Benefits relative to BAU are calculated by expanding the reference system to include multiple buildings in sequence or by changing the unit of comparison to impact per year.	Flexible designs may not be as optimized for an initial use when compared to typical projects.
B2.2 Design for spatial intensification	Design strategies which increase the use or number of possible uses of a building within its lifespan.	OUTSIDE: Benefit measured relative to reference scenario equivalent to larger/multiple buildings.	Reduces the need for additional construction through more efficient space utilization or co-location of uses.	LCA is conducted in typical manner. Benefits are calculated by expanding the reference system to include multiple buildings in parallel or by changing the unit of comparison to impact per unit use.	Strategies which decrease the impact per functional unit may increase the overall life cycle impact.
B3. Strategies that reduce material impacts					
B3.1 Material sobriety and material selection	Strategies which lower the material footprint of a project.	INSIDE: Reduction of burdens in Stage A, as well as B and C in the case of material sobriety.	Reduces material footprint by employing low-carbon materials, or by reducing the overall quantity of materials via increase in material efficiency of components or systems.	LCA is conducted in typical manner. It is important to include any additional downstream impacts potentially induced by unconventional material or design choices, such as more intense maintenance or higher replacement frequency. Different systems may also result in different construction and/or deconstruction impacts.	Low carbon materials may have lower strengths and will be required in larger quantities. Structure as finish may require chemical treatments.
B3.2 Use of materials that store biogenic carbon	Carbon sequestration and storage via the use of bio-based materials.	OUTSIDE: Any benefits should be reported separately from the other modules.	Temporary and/or permanent carbon storage may result in life cycle benefits depending on the assumptions used.	There are many different approaches to accounting for biogenic carbon in a WBLCA. Recommendation of this report is to supplement the National Guidelines with others (ISO 14067, EN 15804).	Effectiveness of carbon storage depends on what happens at end-of-life and only affects the GWP category, also known as, climate change impact category.

Part B -
A Detailed Account of Circular Strategies and WBLCA

Part B contents:

B1. Strategies that share materials across systems

This section covers the circular strategies:

B1.1 Use of recycled materials and reused components

B1.2 Design for deconstruction

B1.3 Renovation of existing buildings

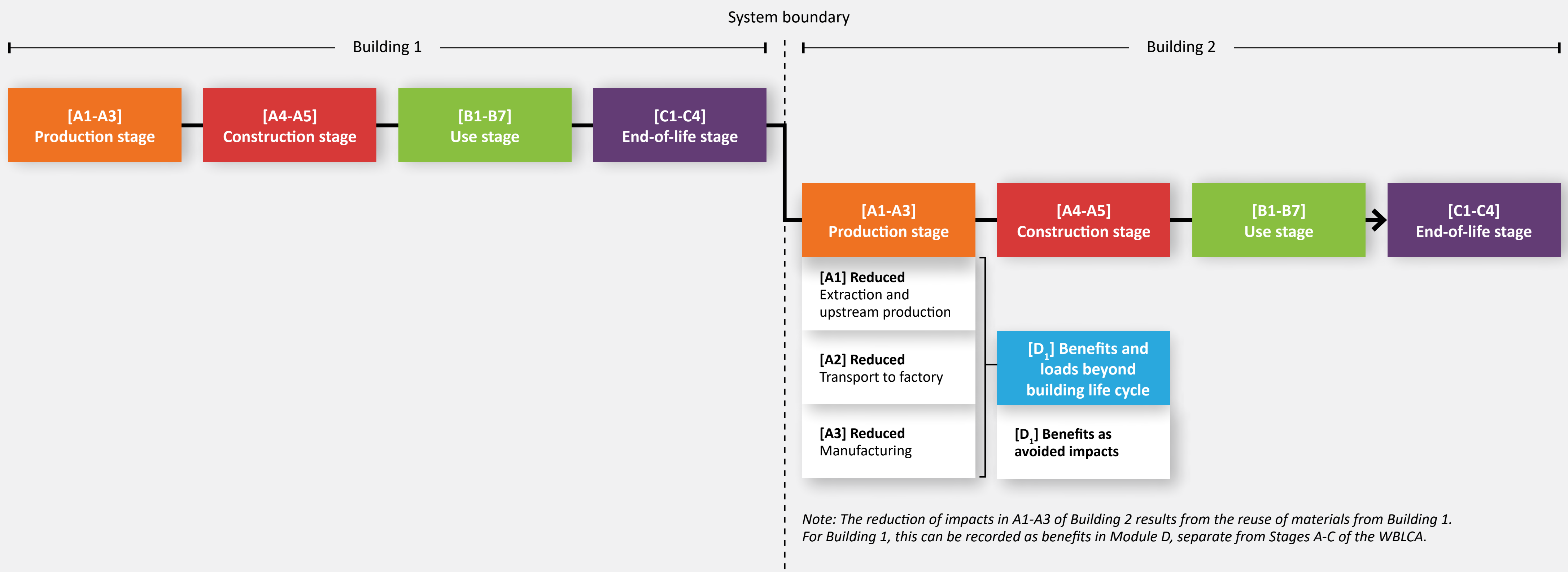
These have been grouped together because they involve materials being shared across building systems. The use of secondary materials in a building project, such as reused and recycled components, results in a life cycle benefit by reducing the demand for primary materials. This reduction in demand may take place in the present or in the future; however, accounting for these benefits within a WBLCA presents several challenges.

Sharing materials between systems introduces a risk of double counting if the same production impacts are counted as part of the construction of multiple buildings. Several allocation methods have therefore been developed to distribute the life cycle impacts of shared materials across multiple systems.

The 100:0 allocation method

The 100:0 allocation method is the most common approach, put forward by ISO and EN standards, and is also known as the cut-off method. In this allocation method, the project that integrates secondary materials (Building 2 in Figure 3) is not responsible for the impacts related to their production (Modules A1-A3) in its own WBLCA, since these have already been allocated to the previous project (Building 1 in Figure 3). As such, Building 2 receives all the benefits of reuse. In addition, if Building 1 had been designed for deconstruction to facilitate reuse of materials and components, the only measurable benefit is a slightly lower end-of-life impact from a reduction in waste disposal.

Figure 3: The 100-0 allocation diagram



Note: The reduction of impacts in A1-A3 of Building 2 results from the reuse of materials from Building 1. For Building 1, this can be recorded as benefits in Module D, separate from Stages A-C of the WBLCA.

It should be understood, therefore, that the 100:0 allocation implicitly favors the use of reused and recycled components over DfD, with Building 2 capturing most of the benefits from material sharing[1,2,3]. Building 1 can record potential reductions from future life cycle impacts through Module D, which cannot be aggregated with Stages A-C of the WBLCA.

Other allocation methods

While the 100:0 allocation is the most common approach in WBLCA, there exist several other allocation methods. These include:

- 0:100 – also known as the avoided burden or end-of-life approach, it is typically used in a recycling context to credit consumer products destined for recycling.
- 50:50 – it favors an equal allocation of burdens between systems.
- Product Environmental Footprint (PEF) – it is a more complex allocation which considers material degradation that is part of a European framework to quantify the impacts of consumer products, including building materials.
- There are other allocations based on physical or monetary quantities, typically applied to manufacturing systems only.

These allocation methods are typically only applied to buildings within academic research literature (though PEF is more common in a European context) and are therefore not covered in the remainder of this report. However, there may be specific cases where it is appropriate to use an allocation method other than 100:0. For example, a project where a temporary structure will be replaced by a more permanent one may be better represented by the 0:100 allocation.

Defining the boundary between systems

There is a point at the end of Stage C where reused and recycled materials transition from Building 1 to Building 2. It is important to define this boundary, as impacts before the boundary are allocated to Stage C of the first building system, while impacts after the boundary are allocated to Stage A of the second building system. These Stage A impacts in the second system are also used to define Module D benefits for the first system.

The boundary between Stages C and A can be ambiguous[4] and should be thought of as the distinction between waste processing and treatment (plus associated handling and transportation) and recycling processes (plus associated handling and transportation).

This boundary state between two systems is also known as the end-of-waste state. As defined in EN 15978, it is reached when “recovered material can be used for a specific secondary purpose, has economic value, fulfills technical requirements, meets applicable standards and legislation, and will not result in adverse environmental or health impacts”. Materials can only exit the system boundary of the first building once they have been appropriately disposed of and/or have value for recycling. This also means that the impacts of handling and transportation, when bridging waste processing, reuse, and recycling activities, are allocated to the second system. In cases where end-of-waste state is still ambiguous, or when waste, reuse, and recycling processes are combined into a single process or chain of processes, the WBLCA modeler will have to explicitly state their assumptions. This is aligned with ISO 14044 which does not provide guidance on boundary definition across systems; rather, it simply requires that decisions and assumptions be clearly documented. Table 4 provides further insights on how the different standards and guidelines address the allocation methods and system boundary definition.

Table 4. Standards and guidelines on strategies that share materials across systems

Standard, Guidelines	Description
WBLCA Standards on allocation methods and system boundary definition	
The National Guidelines	Based on EN 15978, it refers to the 100:0 (cut-off) approach. Any benefits of future reuse should be quantified in Module D. – [6.2] “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).”
EN 15804/EN 15978	It specifies the 100:0 (cut-off) approach. Benefits of reuse should be quantified in Module D. – [EN 15978 Section 7.4.6]: “Module D quantifies the net environmental benefits or loads resulting from reuse, recycling and energy recovery resulting from the net flows of materials and exported energy exiting the system boundary.” It defines an end-of-waste state as the distinction between two subsequent systems: – [EN15804 Section 6.4.3.3]: “The end-of-life system boundary of the construction product system is set where outputs of the system under study, […] have reached the end-of-waste state." – [EN 15804 Section 6.3.4.5]: “The end-of-waste state is reached when any such material or output complies with the following criteria: It is commonly used for specific purposes. There is an existing market or demand for it. It fulfils technical requirements for specific purposes. Its use will not lead to overall adverse affects.”
ISO 21930:2017	It specifies use of 100:0 or cut-off approach. – [ISO 21930 Section 7.2.6] “The allocation procedure for flows crossing the system boundary between product systems (allocation to recycling) is simple. No burdens are allocated across the system boundary with secondary material, secondary fuel, or recovered energy flows arising from waste.” There is no definition of ‘end-of-waste state ’, and it refers to “processing up to the system boundary”.
General LCA Standards	
ISO 14040/14044 ISO 14067	It recommends against allocations in general, but if allocations cannot be avoided, the document provides a definition of closed and open-loop procedures. Only the latter is relevant for construction. – [ISO 14044 Section 4.3.4.3.3/ISO 14067 Section 6.4.6.3] Construction is considered an open-loop procedure as “material is recycled into other product systems and the material undergoes a change to its inherent properties.” The allocation procedure for open loop processes is expressed in ISO 14067 D.4. It does not explicitly define which processes are considered as part of the end-of-life of the original product, or as part of the production stage of the secondary product. However, it specifies that assumptions should be clearly documented. – [ISO 14044 Section 4.3.4.3.2/ISO 14067 Section 6.4.6.3]: “...particularly for the recovery processes between the original and subsequent product system, the system boundary shall be identified and explained, ensuring that the allocation principles are observed as described in [4.3.4.2].”
Product Environmental Footprint (PEF)	The PEF methodology specifies a ‘Circular Footprint Formula’ (CFF) which aims to assess the overall emissions of all processes, including those whose end-of-life scenarios feature reuse, recycling,and incineration. The CFF combines all 3 allocation principles: 100:0, 0:100, 50:50, as well as considerations for material degradation. – [PEF Section 7.7 Handling Multifunctional Processes] Provides a decision hierarchy for modelling multifunctional systems based on ISO 14040: Subdivision or system expansion , then allocation based on physical characteristics, then allocations based on the CFF. This report does not further investigate on the concept of system expansion, since it is a process that mostly applies to closed loop systems. The construction of buildings is considered as open loop. – [PEF Section 7.18 End of Life Modelling] Defines the CFF as well as all its parameters and use cases.

B1.1 Use of recycled materials and reused components

This chapter further describes the approach to use when a building features recycled materials and reused components. With 100:0 allocation, substituting primary materials with secondary alternatives avoids any impacts due to the production of those primary materials. The burdens associated with the initial production of the materials are allocated to the first system (building or otherwise) of which they were a part. The current project should now only consider impacts from recycling or other activities that enable reuse (remanufacturing, refurbishment, repair, etc.) as well as associated storage and transportation activities. This is shown in Figure 4.

Examples:

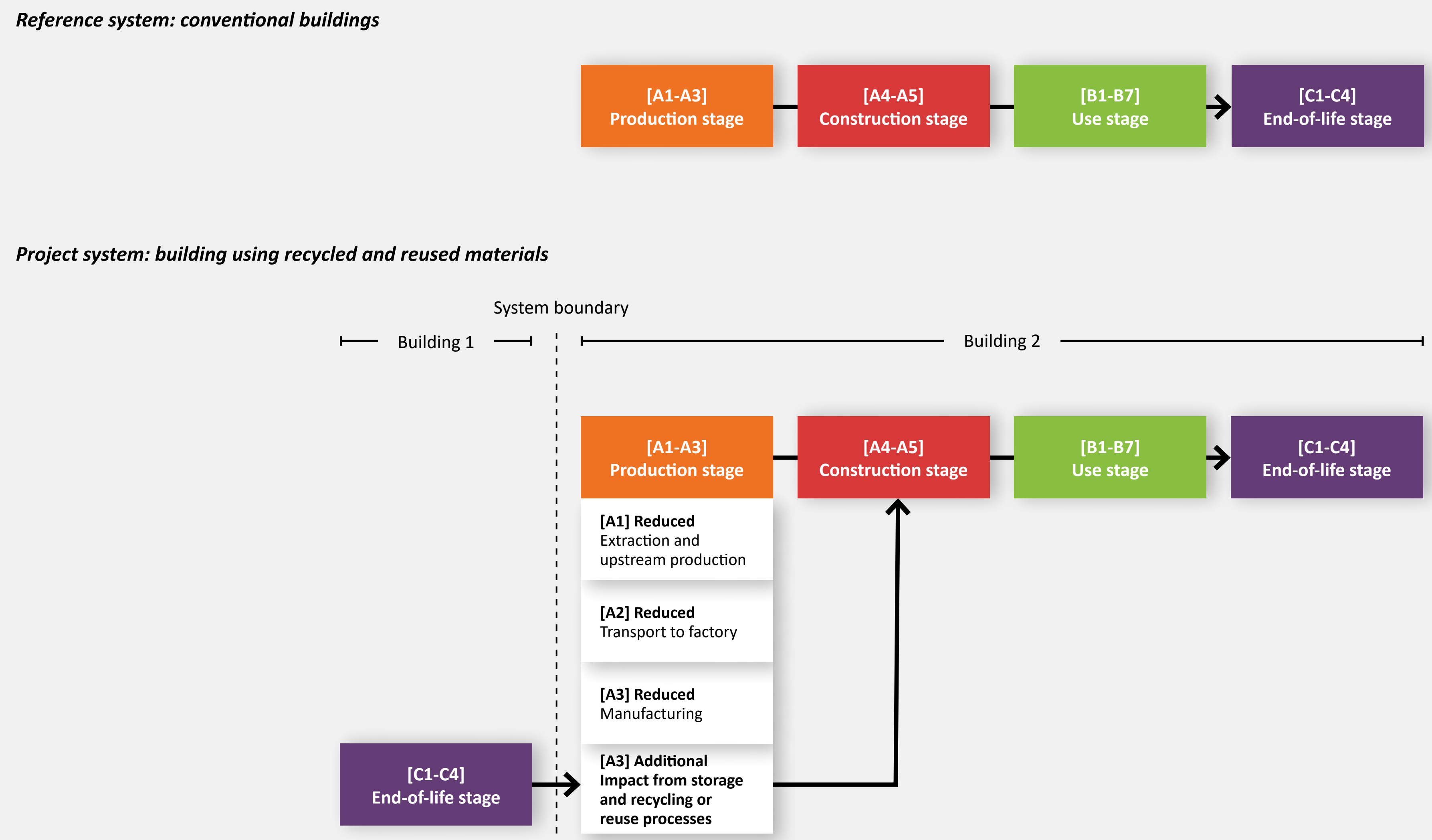
- Recycled concrete debris for backfill or crushed concrete aggregate in new concrete
- Reusing doors, windows, or bathroom fixtures
- Reusing structural components such as bricks, timber or steel beams
- Using building materials with higher recycled content options such as carpet and ceiling tile

How this strategy influences life cycle impacts

The main changes to the WBLCA concern Stage A due to the allocation of production impacts to the previous system. Stage A should now account for all impacts from recycling, refurbishment, sorting, cleaning, and transportation activities. In addition, the reduced service life of many reused components should be accounted for. This is relevant in cases where a reused component necessitates an earlier replacement cycle compared to its newer counterpart, which will affect Stage B.

While it may be possible to replace components with additional reused components, it is unrealistic to assume such a supply chain cycle exists given the current absence of established secondary material marketplaces or ecosystems. Furthermore, there is no clear guidance from existing standards on how to estimate the remaining service life of reused components. Reused components such as windows and doors may also exhibit reduced

Figure 4: Comparison of reference and project systems for use of recycled materials and reused components



Note: The reduction of impacts in A1-A3 of Building 2 results from the reuse of materials from Building 1. For Building 1, this can be recorded as benefits in Module D, separate from Stages A-C of the WBLCA.

Equation 1 | Module A impact (A_{LCI}) for materials with recycled content RC

$$A_{LCI} = E_V\,(1 - R_C) + E_R \times R_C$$

$\mathbf{R_C}$ is the percentage of recycled content within a material. $\mathbf{E_V}$ represents the environmental burdens from acquisition and processing of virgin materials. $\mathbf{E_R}$ represents the environmental burdens from the recycling process of recycled material, including collection, sorting, and transportation.

Formula adapted from JRC Technical Report1 performance relative to newer products and may therefore result in higher heating and/or cooling impacts over the lifespan of the building.

Finally, the use of reused and recycled building materials for structural purposes often requires inspection, structural testing, and certification. This is necessary to ensure the functional equivalence of secondary materials relative to a reference system and for risk insurance. Although there exist certifications guaranteeing the recycled content of materials, there are limited certifications which guarantee the structural performance of reused components. These certifications have begun to be introduced in Europe, such as the CE label for recycled bricks, but do not yet exist in Canada.

How to model this strategy

For Stage A, the modeler should first identify, in the bill of materials, which materials are virgin, reused, and recycled. For materials with a percentage of recycled content, the proportions of primary and recycled content should be treated separately (see Equation 1).

- If an environmental product declaration (EPD) is available for the secondary material, the values of the EPD can be directly used in the WBLCA to replace virgin material impacts. However, EPDs of reused and recycled products are currently uncommon. Since they are based on product LCAs they must contend with many of the same issues as those described in this report.
- If an EPD is not available, or data is not available in Life Cycle Inventory (LCI) databases such as ecoinvent, the new Stage A impact should be determined by calculating the environmental burdens associated with recycling, storage, and transportation processes. These processes should represent the totality of processes which have occurred after the end-of-waste state of the previous product system. Since this is not a standardized method, it is important to clearly document all assumptions. Many standards allow setting A1-A3 to zero while a few standards recommend a 0.2 multiplier specifically for reused components relative to an equivalent virgin product (see Table 5). This is to account for sorting, cleaning, and preparation impacts which are otherwise difficult to account for.

Impacts to Stage B will depend on the availability of data on the relative performance and lifespan of the recycled materials and reused components. This will affect both Modules B4, given the potential early replacement of components, and B6, given the potentially reduced thermal efficiency of the building. Table 5 provides further insights on how the different standards and guidelines address the WBLCA impacts from reuse and recycling.

How to perform a comparison with a reference system

The refence building used for comparative purposes should be identical to the project but built with conventional materials. In addition, the material inputs to the reference building should reflect current practice. For example, if current industry standards already integrate 30% of recycled content in a specific material, then the benefits of using materials with recycled content can only be applied to the percentage that exceeds standard values (i.e., 30% in this case). This is especially relevant for structural steel products, which in Canada vary between 20% and 90% recycled content depending on the manufacturer and the steel making process. Figure 4 compares the stages between the reference and project systems when using recycled materials or reused components.

From the ASCE guide, "[the] team should not take LCA credits for reusing items in the proposed design when the industry standard or contractor preference is already to reuse material (e.g., reusable concrete forming, crushing existing concrete for use as aggregate in site work). WBLCA should include these standard practices in both the reference building and the project design."

Table 5. Standards and guidelines on the use of recycled materials and reuse components

Standard, Guidelines	Description
Standards and guidelines on Module A impacts from reuse and recycling	
The National Guidelines	Modules A1-A3 of recycled materials represent all impacts beyond the system boundary of the previous system. – [6.2] "[The module A impact of recycled products] is the LCI of any further processing of the secondary material occurring beyond the system boundary [of the previous system] that is required to reach the point of substituted functional equivalence"
EN15804/EN 15978	Modules A1-A3 of recycled materials represent the impacts associated with processes occurring after the end-of-waste state. Modules A1-A3 of reused materials are zero.
ISO 21930	It includes processes related to reuse and recycling in Module A1. – [ISO 21930 Section 7.1.7.2.2]: "The information module "extraction and upstream production" covers […] - Reuse of products or materials from a previous product system. - Processing of secondary materials used as input for manufacturing the product, but not including those processes that are part of the waste processing in the previous product system"
Other standards and guidelines	
FutureBuilt Zero[2] (Norway) Milieu Prestatie Gebouwen[3] (Netherlands)	The standards encourage a more detailed calculation of the impacts of reused materials, however if this is not possible, they recommend that Modules A1-A3 for reused materials be set to 20% of an equivalent product, rather than zero.
Zero Carbon Building Design Standard v3 (Canada)	The document stipulates that "to encourage building material reuse, the LCA should include new materials only."
RE2020 (France)	The regulation sets the impact from material reuse to 0 over the life cycle of the project.

Case study | Recycled concrete for structural applications in Switzerland[4]

Use of recycled materials and reused components

An analysis of twelve recycled concrete mixtures was performed and compared to conventional concrete equivalents. The recycled mixtures were defined according to Swiss laws and standards, consisted of 25% and 40% recycled aggregates, and were destined for structural applications. All processes from building dismantling to ready-for-use concrete at the site of construction were included in the system. These included crushing, sorting, and transportation. The analysis found that recycled concrete featured life cycle impacts approximately 30% lower than conventional concrete for many indicators. However, when looking at the global warming potential (GWP), study results did not all converge towards a reduction of GWP impact due to the higher cement content required when incorporating recycled aggregates.

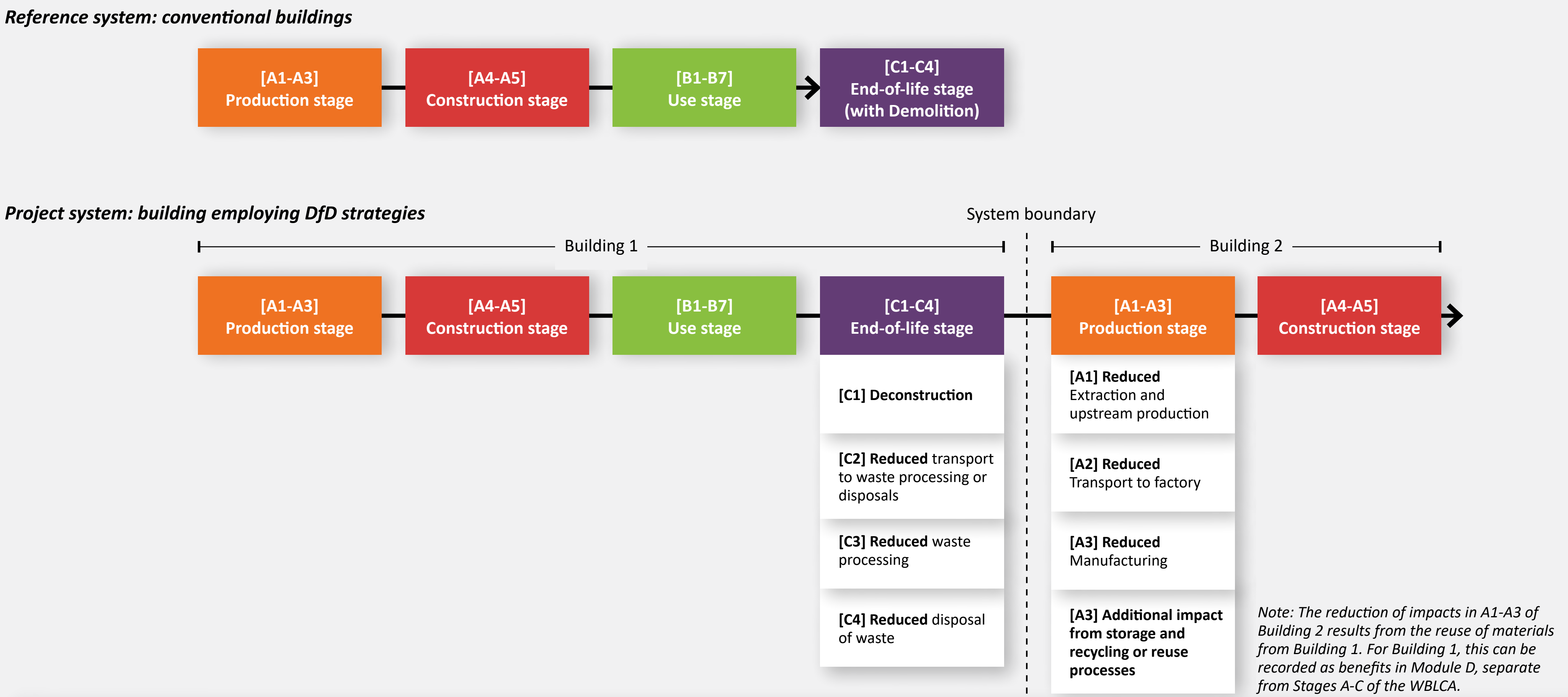
B1.2 Design for deconstruction

Design for deconstruction (DfD) strategies aim to create buildings that can be easily deconstructed to facilitate the reuse of materials and components for future projects. The benefits of future material reuse are quantified in the same manner as the benefits accrued from using reused and recycled materials in a current building project (see B1.1 Use of recycled materials and reused components). The main difference is that these benefits are contingent on many future decisions and actions. Thus, their effect is accounted for in Module D, outside of the system boundary, as opposed to Stage A, as shown in Figure 5. Strategies which promote deconstruction also have a variety of secondary impacts on a building's life cycle impact, and these should also be accounted for.

Examples:

- Reusable modular components
- Mechanical rather than chemical joints
- Separatable building systems
- Avoiding unrecyclable composites
- Information shared from designers to deconstruction contractors to installers in the next building

Figure 5: Comparison of reference and project systems for design for deconstruction



Equation 2 | Module C life cycle impacts (C_{LCI}) for a given recovery rate (RR)

$$C_{LCI} = E_D + (1 - RR)\, E_W + E_S$$

For a given recycling or reuse fraction, or recovery rate **(RR)**, Stage C of a building undergoing deconstruction is the sum of the impacts from deconstruction activities **(E_D)** and the waste disposal impacts for materials still being disposed **(E_W)**. There may also be some additional impacts related to sorting and cleaning recovered materials before they reach their end-of-waste state **(E_S)**.

Equation 3 | Module D benefits (D_{LCI}) for materials which will be reused or recycled

$$D_{LCI} = (RR - R_C) \times (E_R - (E_V \times CF))$$

The benefits reported in Module D are calculated as **(E_R - E_V)**, or the difference between the environmental impacts of recycling processes **(E_R)**, and the impacts associated with the processing of primary materials which are assumed to be substituted **(E_V)**. This value is typically negative. **CF** represents a correction factor (the 'quality ratio') representing any remaining differences in functional equivalence between the reused/recycled materials and the virgin materials.

The term **(RR-R_C)**, where **RR** represents the recovery rate at the end-of-life and R_C represents the recycled content of the original input material, represents the net outflow of secondary material. The National Guidelines provide an illustrative example: if 98% of a steel beam with 90% recycled content is recycled at end-of-life, the net outflow is 0.08kg per kg of steel, and a credit will only be calculated for the 8% difference. Likewise, if it is completely landfilled, then the net outflow is -0.90kg per kg of steel, and Module D will be considered a net burden. The rationale is that secondary steel is being removed from the market, and that this can be considered an additional burden outside the system boundary.

How this strategy influences life cycle impacts

DfD will generate impacts across all stages and modules of the WBLCA. Stage C will be impacted because an increase in the proportion of materials being reused means a decrease in impacts from waste processing, while Module D captures the benefits of displacing primary materials in future construction. Stages A and B may also be affected as a result of design decisions which favor modular construction and separatable building systems; however, these impacts are beyond the scope of this chapter.

The benefits of DfD in both Stages C and D are proportional to the anticipated material recovery rate (RR). The material recovery rate represents the proportion of a material or group of materials which is recovered for reuse or recycling at the end-of-life. Most buildings have some potential for deconstruction and material reuse at the end of their service life. However, buildings designed according to DfD principles feature a significantly higher potential for material recovery. The calculation of this increased potential lies outside the scope of this report and depends on the individual strategies put forward during the design process.

How to model this strategy

Modelling the Module D benefits of DfD requires identifying the materials and components with future reuse/recycling potential. It is not possible to predict which current (non-recyclable) materials will be recyclable in the future. Thus, any assumptions should be based on existing practices and technology, not anticipated ones. Once the reusable materials have been selected, it is necessary to identify the functionally equivalent materials which will be substituted during the construction of future projects. In some cases, reused/recycled materials will substitute new identical products, as is the case with reused brick or recycled steel which display identical performance characteristics to their newer counterparts. However, in many cases, some degree of downcycling is expected due to material degradation. In these instances, assumptions should be made about which products will realistically be substituted.

Under the 100:0 allocation method, the difference between the anticipated life cycle impacts of substituted virgin materials and the anticipated recycling processes

Table 6. Standards and guidelines on design for deconstruction

Standard, Guidelines	Description
Standards and guidelines on the calculation of Module D	
The National Guidelines	The calculation methodology is based on ISO 21930. – [Guideline 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”
EN 15804/EN 15978	Scenarios and assumptions used to calculate Module D should reflect average existing technology and current practice. – [EN 159782 Section 7.4.6]: “Where a material flow exits the system boundary and has an economic value or has reached the end-of-waste stage and substitutes another product, then the impacts may be calculated and shall be based on: – average existing technology; –current practice; – net impacts.” – [EN 15804 Section 6.3.4.6]: “Module D can only be calculated based on a specified scenario which is consistent with any other scenario for waste processing and is based on current average technology or practice.” The document outlines the method of calculation of Module D. – [EN 15804+A2 Section 6.4.3.3] “Allocation procedure for reuse, recycling and recovery in module D the net impacts are calculated as follows: – By adding all output flows of a secondary material or fuel and subtracting all input flows of this secondary material or fuel from each sub-module first (e.g., B1-B5, C1-C4, etc.), then from the modules (e.g. B, C) and finally from the total product system thus arriving at a net output flows of secondary material or fuel from the product system; – By adding the impacts connected to the recycling or recovery processes from beyond the system boundary (after the end-of-waste state) up to the point of functional equivalence where the secondary material or energy substitutes primary production and subtracting the impacts resulting from the substituted production of the product or substitution generation of energy from primary sources; – By applying a justified value-correction factor to reflect the difference in functional equivalence where the output flow does not reach the functional equivalence of the substituting process.”
ISO 21930	The Module D results should not be aggregated with Stages A to C, because Module D lies outside the system boundary. – [ISO 21930 Section 7.1.7.6] “Module D is not a life cycle stage like the life cycle stages assessed in information modules A1 to C4. Module D is outside the system boundary of the studied product system and construction works system. Module D is not an allocation approach and does not report impacts that are allocated to other product systems as a result of co-production or recovery processes. Module D provides optional supplementary information about the potential net benefits from reuse, recycling and energy recovery beyond the system boundary of the studied product system.” It outlines the method of calculation of Module D. – [ISO 21930 Section 7.1.2.6]: “The potential environmental loads and benefits of the net output flow are calculated by: – Identifying the point of substituted functional equivalence where the secondary material or fuel or recovered energy substitutes primary production; – Adding the loads associated with any further processing occurring beyond the system boundary that is required to reach the point of substituted functional equivalence; – Subtracting the impacts resulting from the substituted production of the product or generation of the energy; – applying 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.”

required to bring the secondary materials up to functional equivalence represents the life cycle benefit to be accounted for in Module D. This is represented by the Equation 2 and Equation 3. Table 6 provides further insights on how the different standards and guidelines address the calculation of Module D.

Any remaining difference in functional equivalence between reused/recycled materials and the materials they are substituting is addressed with a correction factor, which is defined by EN 15804 as the 'quality ratio' of outgoing recovered material and the substituted virgin material. Although there is no prescribed way of calculating this ratio, the most common is the ratio in price between the secondary material and the primary material. This inherently depends on the existence of a market for these materials. Other approaches involve comparing mass or other physical characteristics , as opposed to price. It is important to note that EN 15978 specifies that any recycling calculations or credits should be based on net impacts. To calculate the latter, inputs of secondary materials should be subtracted from any outputs of secondary materials. In other words, a project will only see a Module D benefit if it creates more recyclable material than it consumes (see example by Equation 3).

How to perform a comparison with a reference system

The reference building for a DfD project should assume industry standard rates of secondary content for both material inflows (during construction) and outflows (at end-of-life). Both values are needed to calculate a net outflow of secondary materials that is representative of current practice without DfD. Even though the outflows will take place in the future, they should assume only present-day practices and technology. For example, if it is current industry practice for steel inputs to consist of 90% recycled material and for 98% of steel outputs to be recycled (see Equation 3), then the reference building calculation should already include these rates. With Module D calculated for both the project and reference buildings, the benefits of DfD represent the difference caused by an increase in net outflow of secondary materials. Figure 5 compares the stages between the reference and project systems for design for deconstruction.

From the ASCE guide:
"[...] LCA impact factors accounting for reusability may only be applied to components designed for deconstruction in order to enable reuse. For the remaining structural elements, LCA impact factors should be equivalent to those used for the reference building."

"When demonstrating DfD, the reference design should be equivalent to the proposed building, except for components specifically designed to enable deconstruction for reuse at the end of the building's service life. The structural system of the reference building should maintain the same functional equivalence in all other aspects. It should also be of a similar material to the proposed building."

Case study | Concrete frame office building in Italy[1]

Design for deconstruction

Built in 2017, the office building was designed to accommodate 265 working stations over four floors, with a design service life of 60 years. The building features a concrete frame and was designed to take advantage of several innovations in active and passive heating and cooling systems. Anticipated life cycle impacts are dominated by Module B6 (operational energy use), at 60% to 80% of overall impacts depending on the environmental indicator (~70% of GWP). Assuming that steel is recycled at end-of-life at a rate of 70% (rebar) and 90% (sections), and concrete is downcycled as aggregate for roadbeds, the Module D benefits are equivalent to -10 to -15% of the overall Module A burdens, or about -2 to 3% of overall life cycle burdens for the whole building. An analysis by the same authors of a similar office building in Australia, this time featuring a steel frame with composite slabs, reports that the building's Module D benefits for GWP are equivalent to approximately -17% of the Module A burdens for the same building.

Case study | Reusing load-bearing components in a mixed-use building in Switzerland[2]

Design for deconstruction

The case study concerns the design of a smart living lab in Fribourg, Switzerland. The four-storey building is designed to house researchers from several Swiss universities and includes office, residential, and experimental spaces. It is designed to have a very low environmental impact and features a structural system made of wooden columns and beams, as well as concrete slabs, all of which can be easily disassembled. The future reuse of load-bearing components over three consecutive use cycles was projected to reduce the overall global warming potential of the three projects by 39% when compared to buildings constructed with more traditional building systems built from primary materials. The very low anticipated use-phase emissions significantly affected the results.

B1.3 Renovation of existing buildings

Renovations are key to increasing the service life of existing buildings and therefore help to avoid the impacts associated with a new cycle of demolition and reconstruction. However, there are no established guidelines for performing a WBLCA of a renovated building or an LCA of a renovation process (though this is expected to change as European norms governing renovations are currently under development). This is because of the uncertainty around the definition of a renovation system, i.e., which materials and processes should be included or excluded from the analysis. In practice, there are two approaches to performing WBLCAs of renovated buildings and four approaches to performing comparisons with a reference system, as illustrated in Figure 6.

This chapter assumes that the alternative to a renovation is a new building, rather than maintaining the existing building without renovating. The terms retrofit, refurbishment, renovation, and building reuse are often used interchangeably – here the term 'renovation' will be used to capture a broad category of scenarios where a significant proportion of a building is transformed.

How this strategy influences life cycle impacts

While renovations provide significant life cycle benefits relative to maintaining an existing building as-is[1], this chapter compares the impact of this circular strategy to a new construction scenario. On average, renovations result in lower life cycle impacts when compared to new construction. However, reviews of case studies which compare renovation over new construction indicate that this is contingent on many factors, and the outcomes can vary widely[2]. This variation can be explained by the fact that new buildings will likely have lower use-stage (Stage B) impacts in comparison to renovated buildings.

It is important to note that renovated buildings are not necessarily synonymous with lower energy performance relative to new construction, such is the case with passive renovations in accordance with the EnerPHit certification. However, in general, new buildings can better leverage design decisions which maximise efficiency (e.g., orientation, spatial arrangement, passive systems), as well as more advanced building technologies (e.g., integrated HVAC, better airtightness, and glazing). For a renovated building to exhibit a lower life cycle impact than a newly constructed building, the savings that result from the avoidance of demolition and reconstruction should exceed the potential savings from gains in operational efficiency over the lifespan of the new building. This is known as the payback period, and whether the payback period is longer (favoring renovation) or shorter (favoring new construction) than the service life of the new building depends on two main factors:

1. **The energy efficiency of a renovated building relative to new construction:** If a renovated building can achieve energy efficiency gains that are equivalent or close to those of a new building, then the remaining energy efficiency gains from the new construction will not be sufficient to justify demolition and reconstruction. This will depend on the nature and extent of the renovation.
2. **The weight of the use-stage relative to overall life cycle impacts:** If a renovation is not able to approximate the energy efficiency gains that can be obtained from new construction, then the importance of the use-stage relative to other life cycle impacts becomes a deciding factor. If the use-stage only represents a small proportion of overall life cycle impacts, then any energy-efficiency gains from selecting a new building scenario over a renovation will not be sufficient to compensate for the impact of new construction. Conversely, a larger use-stage will increase the chance that new construction will result in lower life cycle impacts.

   The weight of the use-stage depends on three factors:

   a. The anticipated service life: A longer service life will increase the weight of the use-stage, favoring new construction.
   b. The source of the energy being consumed: Cleaner energy sources will decrease the weight of the use-stage, favoring renovations.
   c. The quantity of energy consumed: Lower energy consumption will decrease the weight of the use-stage, favoring renovations.

Case study | Refurbishment of a historic house in Norway[4]

Renovation of existing buildings

Three scenarios were assessed for a 1936 uninsulated timber frame structure: no refurbishment, refurbishment, and new construction. The house represents a common building type from the 1920/30s and, up to its 2014 refurbishment, was heated by an oil boiler and electric radiators before being replaced by a wood stove and heat pump. Results of the analysis showed that refurbishment would result in a reduction in GHG emissions of 67% over 60 years relative to no refurbishment. While some materials were consumed during the refurbishment process, these were dwarfed by a 70% reduction in emissions from energy use. The new construction scenario was projected to result in a further 40% reduction in emissions from energy use, though the large quantity of emissions associated with the new construction resulted in a payback period of 52 years. This means that it would take 52 years of reduced use-phase emissions for the new construction scenario to display lower life cycle emissions than the refurbishment scenario. Over the 60-year reference period, new construction was shown to result in 8% fewer lifecycle emissions than the refurbishment scenario.

Case study | Renovation of 1970s Danish apartment building according to multiple Scandinavian standards[5]

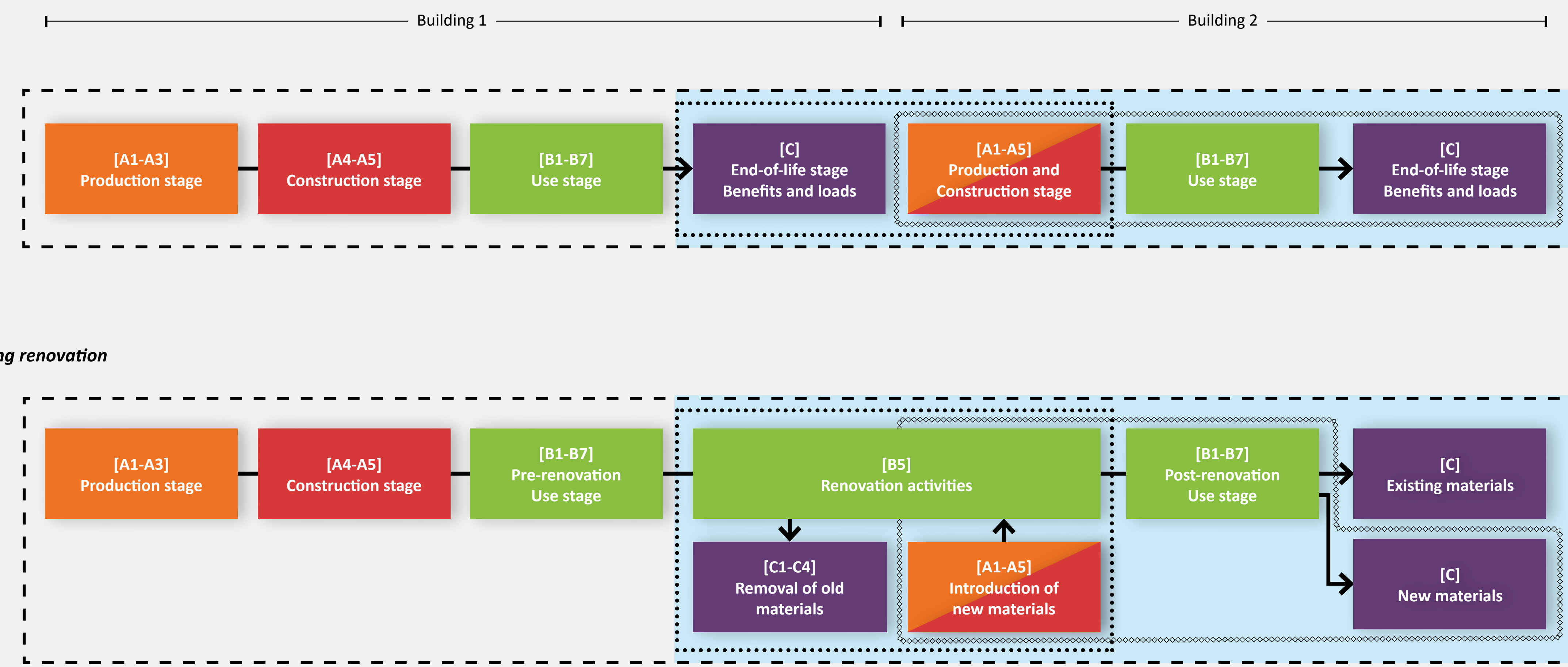
Renovation of existing buildings

An existing four-storey multifamily apartment building is representative of multifamily buildings across Denmark, Sweden, and Finland. The building structure consists of prefabricated concrete components and is heated via district heating. The building was renovated to improve energy efficiency, remove asbestos, and expand balconies. The renovation was compared to a demolition + new construction scenario based on a representative sample of existing projects in the three countries. While all three countries follow the EN European standards, they all adopt different approaches to calculating the life cycle impacts of both the renovation activities and the reference building. The Swedish LCA approach resulted in a 68% reduction in GHG emissions relative to the new construction scenario over 50 years. The Finnish approach resulted in a 32% reduction relative to new construction, and the Danish approach resulted in a 10% reduction. It is important to note that the starting and ending points were not the same across the three countries which affects the results and corresponding significance.

Figure 6: Comparison of reference and project systems for renovation of existing buildings

Reference system: new building on same site

Project system: building undergoing renovation



Four approaches to comparing renovation and new build scenarios:

	Reference	*Project system*
	– Life cycle of two buildings	– Entire lifespan of renovated structure
	– Full demolition – Life cycle of new building	– Partial demolition and renovation activities – Occupation and demolition of renovated building
	– Life cycle of new building	– Life cycle of new components
	– Demolition and reconstruction	– Partial demolition and renovation activities

How to model this strategy

There are four possible methods to perform an LCA for a renovation project. These have been compiled from case studies and the research literature, and they depend on how the system boundary is drawn, as depicted in Figure 6. Although ISO 21930 and EN 15978 do not include guidance on how to model renovations, EN 15978 specifies that the renovation of a building should be accounted for in Module B5 of the original building, supporting method 1) however, researchers and practitioners[3] argue that, in practice, a renovation can also be the beginning of a new life cycle, and that this is in fact compatible with EN 15978. The latter states that if a renovation has not been incorporated into an initial WBLCA, then a new assessment should be carried out. This view is consistent with method 2). Both methods 1) and 2) look at the whole building as a system. On the other hand, methods 3) and 4) focus specifically on the renovation process itself, and of the life cycle of the new components being introduced. In these two cases, the systems being defined do not cover the life cycle of an entire building and are therefore not considered full WBLCAs. However, these two process-LCAs are still useful for comparative purposes when evaluation the subset of a system.

The section below outlines both how to define the LCA system for each approach, and how to define a corresponding reference system.

1. **Renovation as the mid-point of an existing system**

Reference scenario: two buildings on the same site

This approach is aligned with the original intent of EN 15978, which states that all burdens associated with a renovation should be reported as part of Module B5 of the existing building. For this method, the WBLCA covers the entire life cycle of the existing building, and the reference building should therefore include the full construction and deconstruction of two buildings: the existing building and a new building built on the same site. While this is the most comprehensive and simplest approach to clearly define, buildings undergoing renovations are often very old and lack the required quality data to perform an accurate WBLCA of the original system. Thus, this approach is only recommended if there is interest in performing an WBLCA of the original structure, and if there is sufficient and accurate data available to do so.

2. **Renovation as the beginning of a new building system**

Reference scenario: full demolition of existing building + new building

This method assumes that the existing structure is analogous to a reused component in a brand-new building system. It compares the new system (the renovated building) to the construction of a new building on the same site, while also considering the potential savings from the avoided demolition of the existing building. The new system boundary includes all activities from the partial demolition of the existing building until end-of-life of the renovated building, while the reference system boundary includes all activities from the full demolition of the existing building until end-of-life of a fictitious new building.

3. **Renovation as new components in an existing building**

Reference scenario: new building

In this third approach, only components added during the renovation are part of the new study system, and any components carried over from the existing building are still considered to be part of their original building system. The comparison is strictly limited to these new components, relative to the construction of a new building. Here, the partial demolition of the existing structure is not included, nor are the demolition impacts of the materials that came from the existing building. This is the approach briefly mentioned in the ASCE guide: “In cases where the project involves reusing an existing building, the WBLCA should include only the elements newly brought to site, plus the burdens from any on-site repairs and demolition.”

4. **Renovation activities**

Reference scenario: demolition + reconstruction

This approach is the simplest of the four and may be appropriate if the renovation results in minimal changes to the building. The comparison is strictly limited to the impacts from renovation activities versus the impact from a cycle of demolition and reconstruction. This approach assumes that the use-stage impacts of the renovated building are comparable to the use-stage impacts of a new building. It is a useful method to compare a partial demolition with a full demolition without the required effort to consider impacts beyond the renovation activities. As mentioned, this approach is a process-LCA which does not consider all the stages and modules.

Case study | LCA impacts of four types of renovations in a Swedish apartment building[6]

Renovation of existing buildings

A three-storey residential building from 1971 containing 36 apartments was used as a case study comparison of four approaches to renovation. These approaches varied in their degree of material intensity, with combinations of changes to the building envelope and heating systems. The analysis is limited to the lifecycle impacts of the renovations themselves, relative to the existing building. All scenarios featured additional lifecycle impacts from the components introduced during the renovations, which were offset by reductions in energy consumption over the 50-year study period. A renovation which combined updates to both the envelope and heating system resulted in the largest reduction in lifecycle impacts (-19%), followed by updates to only the heating system (-16%) and updates to only the envelope (-6%).

How to perform a comparison with a reference system

The content of this section has been explored in the above section. Figure 6 compares the stages between the reference and project systems for renovations.

B2. Strategies that increase building utilization

This section covers the circular strategies:

B2.1 Design for longevity

B2.2 Design for spatial intensification

Another approach to lower new-construction impacts is to avoid the need for further additional construction by maximising the use of the buildings that do get built.

This section covers two forms of increased building utilization: **temporal** by extending the service life of buildings and **spatial** by increasing the density and number of activities within the space. WBLCAs of buildings designed to these ends should be conducted as usual, according to existing standards and guidelines. However, the quantification of the overall benefits from increased building utilization requires a different approach because they exist outside the building boundary system.

This requires comparing the project to a BAU reference scenario that is not directly functionally equivalent.

As outlined in Part A of this report, the ASCE guide does not allow for any functional difference between the project and its reference building. The only exception is for changes to structural systems since such changes remain aligned with the intent of the LCA. The guide also implicitly assumes that the unit of comparison is the entire building. While the approach outlined in the ASCE guide is detailed and comprehensive, it does not allow for a WBLCA to capture the benefits of an increased service life or an increase in the density of activity. These benefits can still be calculated by using the normalization approach that is commonly used by practitioners to compare different unrelated case studies. This approach involves changing the unit of comparison, or functional unit, from the entire building over its full lifespan to an alternative unit, such as the impact per year of occupancy or impact per unit of activity. The concept of a functional unit is defined in ISO 14040/44, which specifies that "[the] functional unit shall be consistent with the goal and scope of the study." Indeed, it is sometimes argued that selecting an alternative functional unit stays true to the intent of the ASCE guide because it maintains functional equivalence between project and reference systems, the equivalence being between functional units rather than between the buildings themselves.

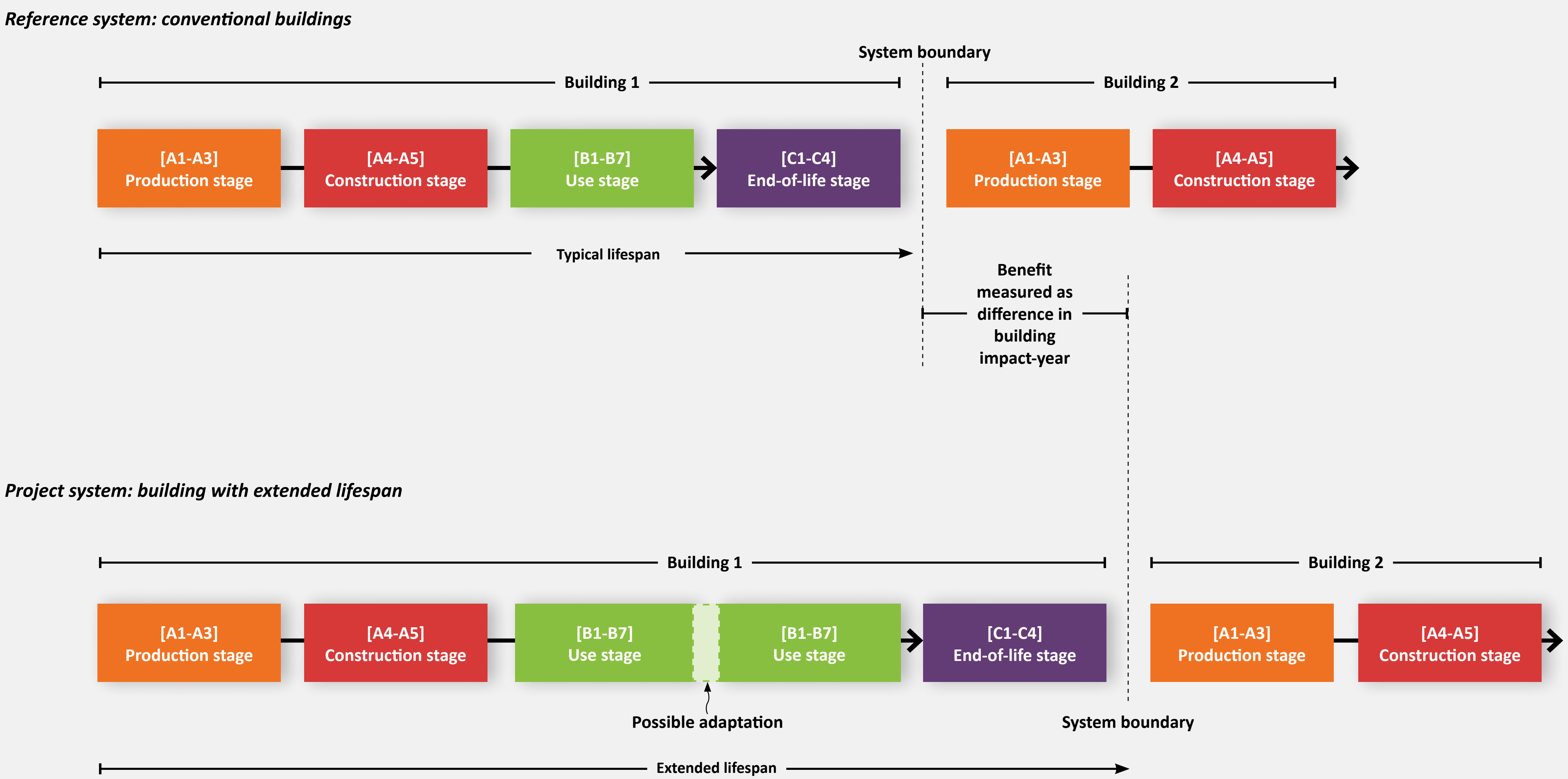
B2.1 Design for longevity

As is the case with renovations, a building designed with a longer service life helps to avoid or displace new construction, which would usually occur after the end of a typical building lifespan. Several decisions can be made during design and construction to increase anticipated service life. These encompass both small-scale design decisions, such as using components that last longer, and larger ones, such as designing for adaptability. In both cases, the life cycle benefit comes from extending a building's life expectancy, as shown in Figure 7. Both approaches are explored in this chapter. WBLCA modelers do not need to modify their approach for the assessment. However, they will need to adjust the reference building or use a different functional unit for comparison to account for the circular benefits. This report does not look into design for resilience as part of design for longevity. This would require the reference building to include the replacement and repair due to damage expected in a conventional design, which can be at odds with material sobriety.

Examples:

- Small-scale interventions:
  - Longer-lasting components and materials
  - Standardized components that can be easily replaced
  - Pre-emptive maintenance
- Design for longevity:
  - Multifunctional spaces
  - Design for repairability
  - Reduced complexity
  - Separated and easily-accessible building systems
  - Modular building systems
  - Non-load bearing partitions
  - Climate resilience

Figure 7: Comparison of reference and project systems for design for longevity



How this strategy influences life cycle impacts

The circular strategy of increased building utilization by extending the service life of a building does not affect the WBLCA as a whole. The difference lies in how the reference building is defined and how the WBLCA results are reported.

How to model this strategy

The circular strategy of increased building utilization by extending the service life of a building does not affect how one performs the WBLCA. The reporting of results, however, requires different functional units for proper comparison to account for accrued benefits. Further explanation is given in the next section. The section below outlines both how to define the LCA system for each approach and a corresponding reference system.

How to perform a comparison with a reference system

There are several approaches to comparing buildings or systems that differ in their study periods. The ASCE guide avoids any difference in functional equivalence via a prorated use phase. The guide states that "[the] reference study period should be the same for the reference and proposed buildings. If the reference building has a different service life than the proposed building, the use-phase impacts of the reference building may be prorated accordingly." In this case, the reference building for a project that is designed to exhibit a 50% longer lifespan will also have its use-stage, as well as corresponding use-stage impacts, increased by 50%. The drawback of this method is that it does not result in any benefits for a building built for longevity, as compared to an equivalent building designed for a typical lifespan of a BAU scenario, as it will display an unrealistically longer lifespan without any accompanying design or construction changes. However, there are approaches that capture the benefits from increasing the longevity of a building:

1. **Selecting a time-based functional unit for comparison (recommended)**

   For this approach, the functional unit is set to impact per year of building operation (for a GWP example: $kgCO_2e/yr$). Since the construction (Stage A) and end-of-life (Stage C) impacts of a building with an extended lifespan are spread over a larger timeframe, the normalized yearly impact decreases. The impact per year of operation is calculated by dividing the overall life cycle impacts by the building's lifespan. The calculation should be completed for both the project and the reference building. The difference is then reported as a percentage.

2. **Defining the reference system as two or more sequential buildings**

   This approach is equivalent to the first approach discussed in B1.3 Renovation of existing buildings. Here, the reference system is expanded to include multiple buildings built in succession on the same site. In this approach, the unit of comparison is not the building itself but the use that can be obtained from it over a specific period of time. This approach is applicable when the anticipated lifespan of the project is extended to over double the lifespan of a typical reference building. A building's typical lifespan is 60 or 75 years, depending on the standard and WBLCA tool. The design of any subsequent buildings should be identical to the first.

3. **Defining the reference system as a typical structure with additional repair and maintenance impacts**

   This approach assumes that a building designed with an increased life expectancy is equivalent to a typical building except that the typical building would require additional repair, maintenance, and replacement impacts to achieve the same lifespan (Modules B2-B5). This is appropriate for projects designed to minimize their anticipated maintenance and repair impacts over time without making significant changes or refurbishments.

Figure 7 compares the stages between the reference and project systems for design for longevity.

Case study | Effect of longevity on the LCA impacts of Danish building components[1]

Design for longevity

A study was conducted for seven representative categories of building components, including external and internal walls, roofs, windows, and foundations. The study assessed the environmental benefit obtained for each category of component if the lifespan of the building is extended from 50 years (typical reference lifespan for a building), to 80, 100, and 120 years. Impacts were assessed for seven environmental impact categories and were measured in terms of impact/year, meaning that for longer building lifespans the impacts associated with the components would be spread over a longer period of time. Results showed that when compared to a lifespan of 50 years, a building lifespan of 80 years reduced the impacts/year by 29%, 100 years by 38%, and 120 years by 44%. This was the case for all components except for windows and roof lights. Their lifespans were shorter than the lifespan of the building housing them, and therefore needed to be replaced.

B2.2 Design for spatial intensification

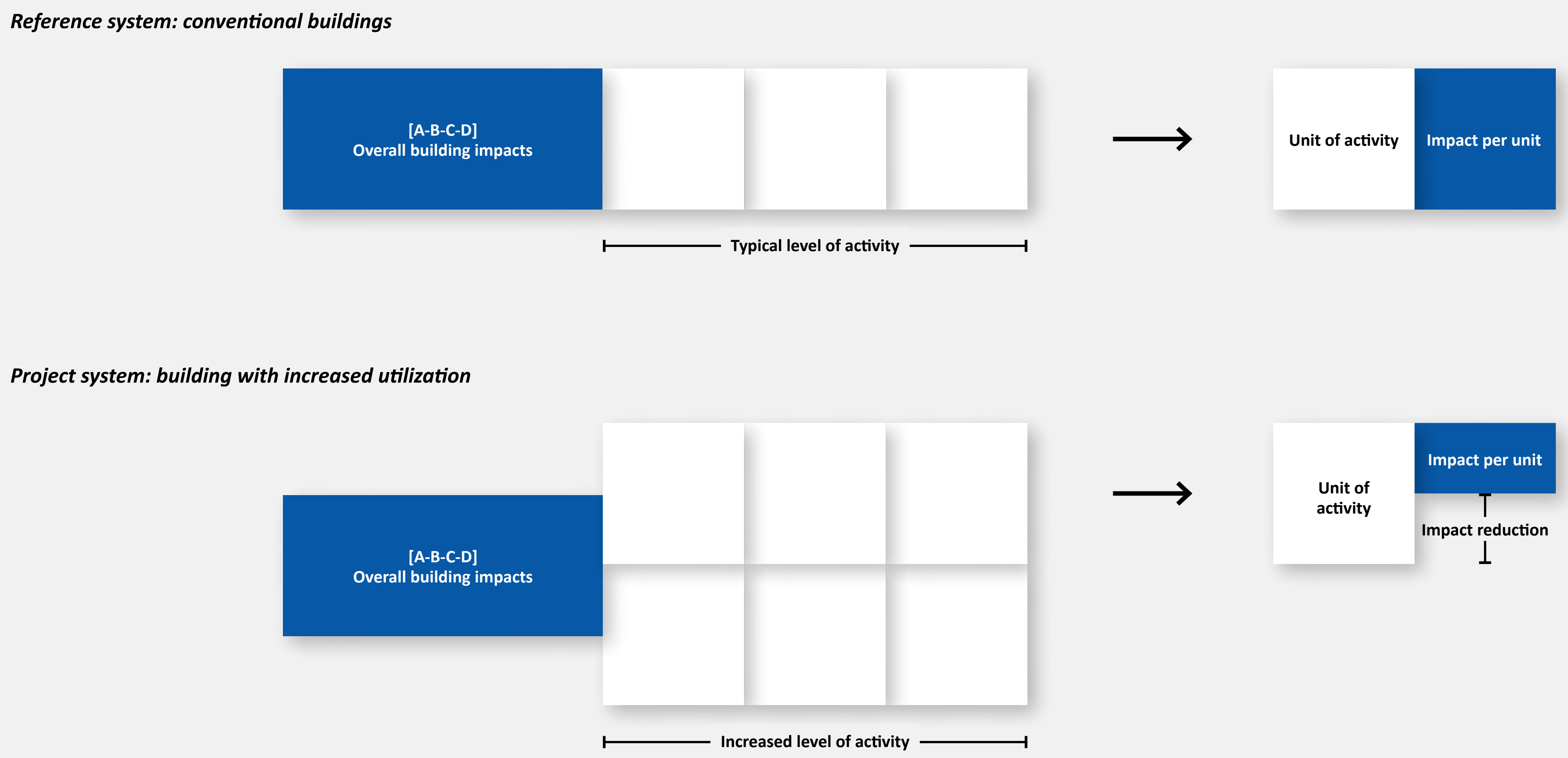
Reducing the demand for new construction outside the system boundary can occur simultaneously, not merely sequentially (see B2.1 Design for longevity). Designing spaces to accommodate increased activity or multiple different activities reduces the demand for additional construction. In practice, the benefits of this circular strategy translate into a reduction in life cycle impacts per unit of activity. In this context, activity is a unit that represents the number of building users, number of residential units, or the space available for productive use. Design changes that increase the number of shared spaces, the number of residential units, or the amount of usable floor area while keeping a fixed quantity of building materials are examples on how to achieve spatial intensification. For an increase in floor area to result in a life cycle benefit, it is necessary to maintain the same density of activity per unit of floor area, as opposed to simply increasing the area available per user.

As with B2.1 Design for longevity, the WBLCA is performed as usual but the benefits relative to a BAU scenario are calculated by adjusting the reference system or using a different functional unit for comparison, as shown in Figure 8. Because the benefits of displaced construction occur outside of the building system boundary, they can only be accounted for in Module D of a traditional WBLCA.

Examples:

- Multifunction spaces
- Co-location of different uses
- Changes in spatial arrangement to maximise floor space
- Mobile partitions

Figure 8: Comparison of reference and project systems for design for spatial intensification



How this strategy influences life cycle impacts

The circular strategy of spatial intensification does not affect the WBLCA as a whole. The difference lies in defining the reference building and reporting WBLCA results.

How to model this strategy

The circular strategy of spatial intensification by increasing building utilization and spatial density does not affect how one performs the WBLCA. The reporting of the results will, however, require different functional units for proper comparison to account for accrued benefits. Further explanation is given in the next section.

How to perform a comparison with a reference system

As with B2.1 Design for longevity, the ASCE guide does not accept anything beyond minor differences in design criteria, nor any decrease in building performance:

"When feasible, the values associated with all design criteria should match between the two designs [and] for the proposed building to be considered functionally equivalent to the reference building, it should meet or exceed the minimum performance standards [...] of the reference building. The proposed building may exhibit improved performance over the reference building as long as the WBLCA includes the life cycle impacts from the materials used to achieve the improved performance. However, the proposed building may not exhibit decreased performance than the baseline."

This means that defining a reference system for an 'intensified' project, which typically involves changes to the building program, according to the ASCE guide, will not effectively represent the BAU scenario. The reference system will be too similar to the new project being proposed. If a reference system is chosen to accurately represent what would typically be built on a given site, then it will contravene the recommendations of the guide. Any comparisons between project and reference systems that differ in their programs will, therefore, lie outside the scope of the ASCE guide.

The two approaches below describe methods for comparing a project to a reference scenario for quantifying the benefits of the intensification strategy.

1. **Normalizing results with an activity-based functional unit (recommended)**

   As with B2.1 Design for longevity, selecting an activity-based functional unit, also known as a normalization unit, reflects the fact that a project's life cycle impacts are spread over a larger quantity of activity compared to BAU. Unlike B2.1 Design for longevity, there are several possible units of comparison depending on the nature of the construction. The calculation should be completed for both the project and the reference building. The difference is then reported as a percentage. Note that each unit of activity can be calculated multiple ways: square meters can refer to gross floor area, gross livable area, or heated floor area[1]. Any given study should maintain strict consistency in the way the functional unit is defined across scenarios.

   The functional unit selected for normalization may also affect the results of any comparison if the designs diverge beyond a certain point. In the case of a residential building, selecting 'impact per unit' will favor buildings with smaller, denser units than buildings with multi-bedroom units, while selecting 'impacts per area' will favor buildings with larger, less space-efficient units[2]. For example, when evaluating the impacts of Stage B, some impacts are linked to physical space (ex: replacements) and some to resource use (ex: water, energy). If the number of residents is doubled for the same design, the impact per resident in Stage A is reduced by 50%. However, the impacts in Stage B will not be reduced similarly due to use of energy and water.

2. **Comparing a single mixed-use building to a scenario where uses are housed separately**

   Similar to B2.1 Design for longevity, the reference system is expanded to include multiple buildings. However, in this case, the buildings are built in parallel. The intention is to represent the many uses or activities planned for the new building across individual buildings if these uses would typically have been housed separately. This approach is more appropriate when multiple different uses are combined into a single project.

Table 7. Examples of design strategies and their corresponding unit of activity

Design strategies by building type	Unit of activity
Design strategies that increase the number of units in a residential building.	– Impact per residential unit – Impact per bedroom – Impact per resident
Design strategies which increase the occupancy of any building, be it residential, office, or commercial/ institutional	– Impact per area – Gross external area – floor-area measurement including walls and structure – Gross internal area – floor-area measurement excluding walls and structure – Gross floor area – areas included and excluded defined in the National Guidelines – Gross livable area – excluding maintenance and otherwise inaccessible areas – Heated floor area – relevant when projects have a large use-phase component – Rentable area – only including the inside of residential units – Impact per unit of volume (m^3) – Impact per expected occupant – Number of occupants based on building code/egress requirements – Number of occupants based on ventilation requirements – Full-time equivalent

Note: All of the above may also be assessed on a yearly basis: Impact per area per year, impact per occupant per year

Figure 8 compares the stages between the reference and project system for design for spatial intensification and the importance of the activity unit to showcase potential benefits.

B3. Strategies that reduce material impacts

This last section covers the circular strategies:

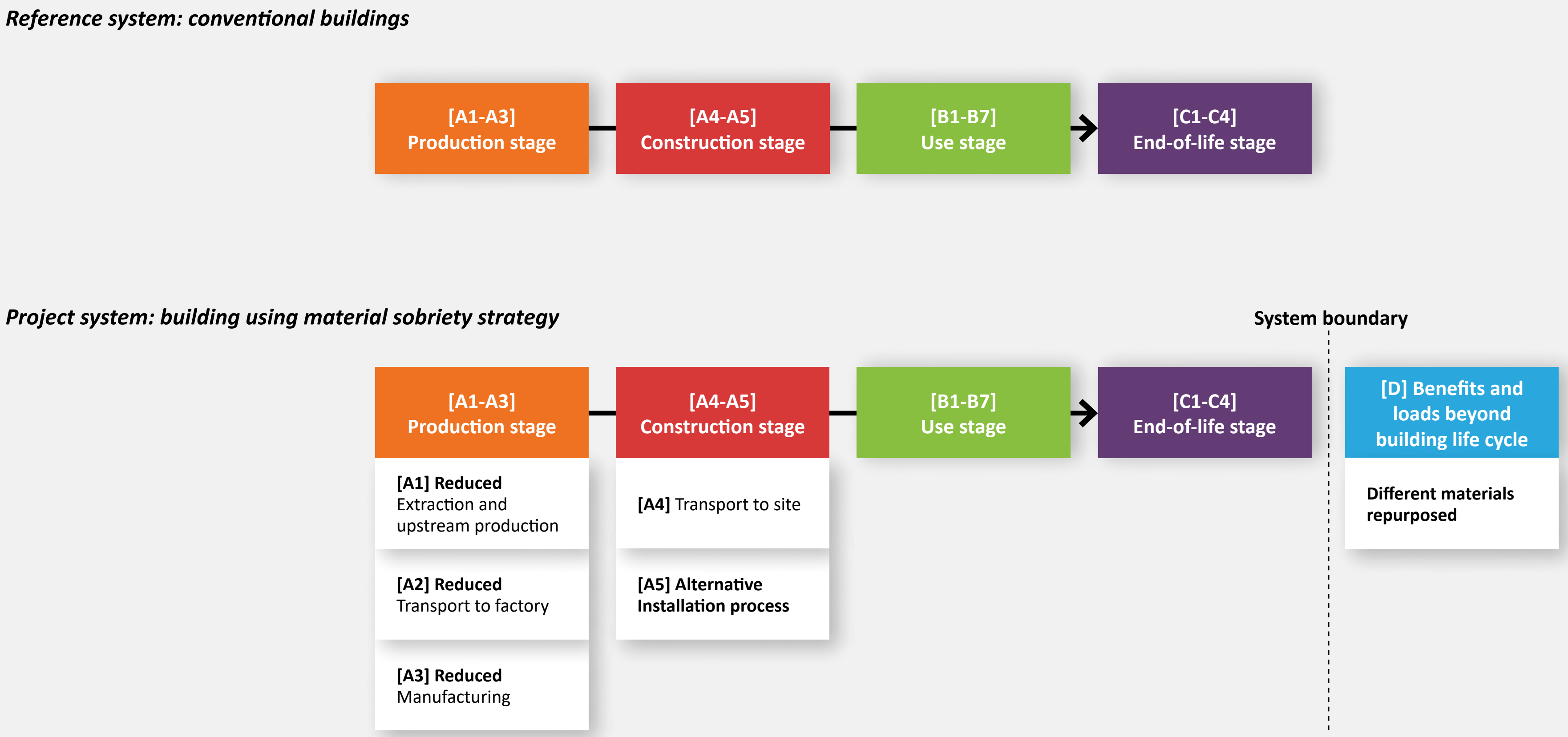
B3.1 Material sobriety and material selection

B3.2 Use of materials that store biogenic carbon

Design decisions intended to reduce required material quantities and to influence material selection can reduce life cycle impacts of the production stage (Modules A1-A3) with downstream effects in other LCA stages within a system's boundary.

This can be achieved through the selection of low carbon materials or the overall reduction of material quantities through lean and efficient design. Such strategies help reduce the demand for primary building materials but also encourage the use of less impactful ones. Finally, bio-based materials, such as engineered-wood, can display auxiliary benefits in carbon storage, known as biogenic carbon. Since this is a controversial topic, the report outlines the considerations and complexities of accounting for biogenic carbon.Strategies that reduce material impacts can come into tension with other circular strategies that focus on adaptability and flexibility. The latter typically requires some degree of over design to accommodate for potential future growth. This example highlights that circular strategies do not all operate in synergy with each other. Tensions exist and some design decisions will lead to trade-offs. It is thus key to weigh strategies against each other and BAU scenarios. In the case of reducing material impacts, projects that employ conventional material products will become the reference system for comparison.

Figure 9: Comparison of reference and project systems for design for material sobriety and material selection



B3.1 Material sobriety and material selection

Material sobriety refers to the net reduction in material quantities, which, in return, lowers the life cycle impacts of a building, as represented in Figure 9. On the other hand, material selection refers to the choice of materials—such as low-carbon materials—that yield lower environmental impacts compared to typical or BAU construction materials in their EPD. Both strategies can overlap in their implementation. For example, a lightweight structural system built with high-strength materials can be considered as an example of material sobriety (lightweight) and as an instance where material choice was important (high-strength steel produced via electric arc furnaces). Because both approaches are accounted for in Modules A1-A3, usually with the support of EPDs, and share the same method of defining a reference system, they are combined in this chapter.

Examples

These can be thought of as existing along a spectrum of material selection to material sobriety

- Material selection:
  - Low-carbon steel
  - Low-carbon concrete
  - Bio-based materials
  - Mass timber
  - Engineered-wood products
- Material sobriety:
  - Reduce redundancies
  - Reduce waste via prefabrication and plan of layout and specifications
  - Reduce building dimensions through optimization
  - Reduce underground or high-rise construction
  - Structure as finish
- Combination of both:
  - Higher-strength materials
  - Post-tensioning
  - Voided slab

Examples cont.

- Advanced structural systems
- Composite materials

How this strategy influences life cycle impacts

Accounting for material sobriety and material selection does not impact the WBLCA methodology articulated by current standards and guidelines. However, practitioners should keep in mind that it may be more difficult to obtain EPDs for less conventional products. Moreover, certain design decisions (ex: structure as finish or new composite materials) can result in additional impacts that are not typically included in BAU scenarios. Some examples of tensions within these strategies are outlined below. It is important to find a balance between the benefits and impacts for a project.

- **Material finishes:** To comply with fire, durability, and vibration requirements, an exposed structure requires special finishes and treatments. The WBLCA should include these products. For example, engineered-wood products are treated to prevent deterioration and exposed timber is protected with intumescent coatings for fire protection.
- **High-strength materials:** High-strength concrete mixes and high-strength steel products can reduce the required net material quantity, but they can also have higher life cycle impacts than their BAU counter products.
- **Advanced components:** Post-tensioned, prefabricated, and voided concrete slab systems reduce the overall volume of concrete used. However, they will require alternative assembly and construction methods, which must be accounted for in Module A5. Their production impact might also differ from standard products.
- **Component replacement and repair:** Lightweight components may exhibit a lower service life than conventional components and will therefore require more frequent replacement cycles or will require more maintenance and repair. Such impacts should be accounted for.

Material sobriety can exist in tension with design for adaptability, which is a subset of design for longevity. Design for adaptability involves a degree of over-

Case study | Addition to school in Québec using mass timber construction[1]

Material sobriety and material selection

The project in Montreal includes two stories of classrooms and a gymnasium for a total of 2,425 m2 of floor area. Design includes concrete foundations, a light wood structural system, glue laminated timber components and prefabricated wood roofing. An analysis performed using the Gestimat tool showed that when compared to a steel-frame reference design, the project features an overall reduction in embodied GHG emissions of approximately 50%.

Case study | Review of low-carbon construction materials[2]

Material sobriety and material selection

A review was conducted on the reductions in GHG emissions that can be expected via the use of alternative construction materials. Concrete, for example, requires the intermediate production of a cement clinker—essentially limestone and other minerals transformed by heat—which typically produces large volumes of CO_2 both from the chemical process and generation of heat required. Alternative approaches to produce clinker can reduce emissions by 12%-15%, or even up to 40%, depending on the approach taken, though this may result in a loss of performance. Meanwhile, the alternative use of natural materials such as wood, soil, clay, or hemp may result in large reductions in emissions of 60%-90% and may feature the additional benefit of biogenic carbon storage. Local materials significantly cut the transportation element of the material's environmental footprint in a manner proportional to the reduced distance travelled. Finally, selecting high-performance materials and optimizing designs can reduce material requirements, and therefore production emissions, by up to 30%.

engineering so the structural system can accommodate potential future loads greater than the current requirements. This is in contrast with material sobriety approaches, which focus on reducing the quantity of unnecessary materials for the desired function by fully optimizing the structure for a specific use and context. This leads to a more efficient design and can result in mixed-use spaces and the selection of lighter components. It is possible to create a building that combines both design for longevity and material sobriety strategies, notably through the implementation of large mixed-use spaces. However, in practice there is often a trade-off between both approaches.

How to model this strategy

This strategy does not impact the standard WBLCA methodology. Material sobriety and material selection will mostly influence the results of Stage A of the life cycle. The practitioner should look out for any design repercussion from implementing such material strategies, as explained above.

How to perform a comparison with a reference system

The ASCE guide outlines specific considerations for performing effective comparisons between projects and reference systems that differ in their material quantity or selection. These are outlined in the five chapters of the guide: *Structural Material Quantity Reduction, Structure as Finish, Nonstructural Material Quantity Reduction, Impact Reductions Achieved by Using Alternate Structural Systems, and Impact Reduction of Functionally Equivalent Materials.* The following points summarise the guide's recommendations:

1. **The reference system should faithfully represent standard industry practice.**

   The ASCE guide states that:
   "The user should not indicate a reduction in material quantities for the proposed systems when the industry standard is a more efficient system (e.g., if post-tensioned slabs are the standard for multistory residential construction, the team cannot utilize a mildly reinforced concrete slab for the reference building and a post-tensioned slab for the proposed)."

   "The reference building design should consider industry-standard impacts for the building type as they pertain to the envelope, finishes, and MEP systems."

2. **The project and its reference system should be as functionally equivalent as possible. Any discrepancy in functional equivalency can only be directly related to the difference in material use, finish, or structural system.**

   The ASCE guide states that:
   "The project team should ensure that the building's bay size, programming, and loading are as equivalent as possible to the proposed building."

   "To qualify as an acceptable proposed building with exposed structural elements, the building should be functionally equivalent to the reference building with structural elements covered with finishes, where the application of those finishes is industry standard."

   "In demonstrating reduced environmental impacts, often as a result of integrated design, the WBLCA should show that the reference building design is equivalent to the proposed building, except for the reduced material in the envelope, finishes, and/or MEP systems when the structure provides certain functions for these systems instead."

   "Because this strategy involves comparing alternate structural systems, there will be significant differences between the reference system and the proposed system. However, both systems should have similar, or improved, BOMs compared to industry benchmarks, or other archetype data."

3. **Any impacts associated with new materials or less conventional products should be taken into account.**

   The ASCE guide states that:
   "The WBLCA should account for any increased environmental impact resulting from the manufacture of the higher-strength material."

   "In many cases, an exposed structure requires additional maintenance compared to a covered structure, although in some cases the opposite is true. Regardless, the WBLCA model should consider the impacts of maintenance or replacement through the reference study period of the LCA."

   "If the alternative materials or systems used in the proposed building have a shorter lifespan than the design lifespan of the proposed building, the WBLCA should include impacts for the repair and/or replacement of the material or system."

Figure 9 compares the stages between the reference and project system for material sobriety and material choice.

B3.2 Use of materials that store biogenic carbon

While the storage of biogenic carbon is not directly related to circular-economy strategies, it is an important secondary outcome of the switch from conventional construction materials to renewable bio-based materials. This chapter will therefore explore the implications of including biogenic carbon in a WBLCA. Bio-based materials, such as engineered-wood, can not only exhibit lower life cycle impacts compared to industry-standard concrete and steel (see B3 Strategies that reduce material impacts), but they also provide the benefit of carbon storage (temporary or permanent) in the biomass accumulated during the growth process. In nature, this biogenic carbon is released when the plant dies and decomposes. In construction, biogenic carbon is typically released at the end-of-life of the building through burning or transformation. These biogenic carbon flows are shown in Figure 10. There are several ways to account biogenic carbon in a WBLCA, but there is no consensus so far on how to best report it. Different tools include and report biogenic carbon in different life cycle stages and modules, which makes it difficult to compare results across tools and projects. This chapter covers the challenges to incorporating biogenic carbon in WBLCA, as well as a recommended approach.

Examples

- Light structural-wood construction
- Cross-laminated timber products
- Glue-laminated timber
- Laminated-veneer lumber
- Straw and hemp for insulation

How this strategy influences life cycle impacts

There are several factors that complicate an assessment of the life cycle impacts and benefits of biogenic carbon storage:

- **Storage is mostly temporary**
  Wood-based products act as temporary carbon sinks and, as such, they do not represent a permanent solution to remove or avoid carbon emissions. They nevertheless provide a benefit by buying time to figure out mitigation measures and to avoid an early peak in global warming. The quantification of the benefits from the temporal displacement of GHG emissions is an evolving field with no current consensus, which is an issue when aiming for coherent WBLCA practices.

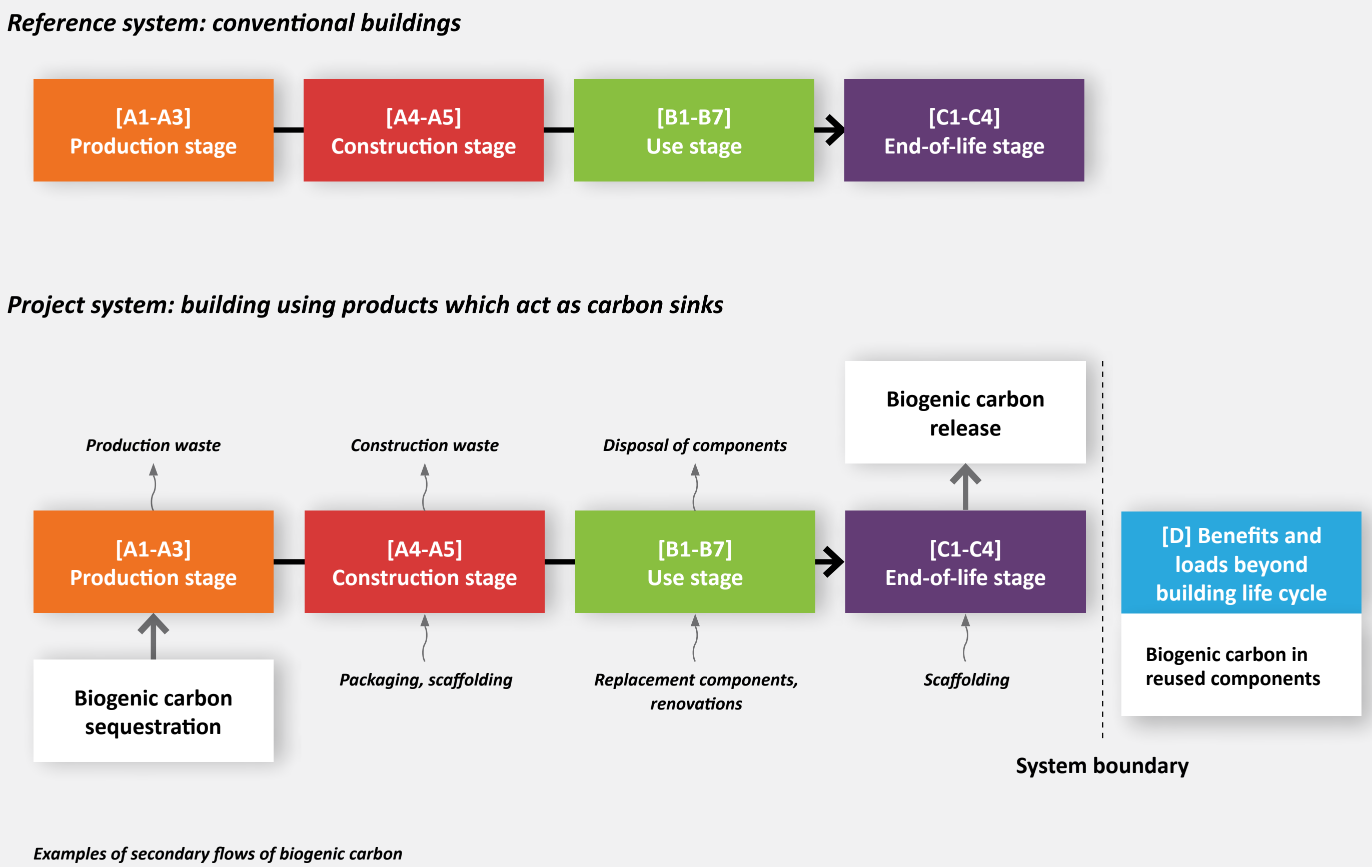
- **Benefits are dependent on end-of-life conditions**
  Even when it is argued that biogenic carbon can be locked in permanent storage, it is difficult to assess which proportion is locked and for how long. Such determinants are contingent on the method of disposal at the end-of-life (ex: combustion, decomposition, anaerobic vs aerobic landfills) and are therefore inherently uncertain.

- **Land-use impacts are difficult to quantify**
  The harvesting of wood has extensive land-use and land-use-change (LULUC) impacts. Direct impacts can be mitigated by requiring sustainably harvested wood, though there is no broadly accepted method for evaluating indirect impacts.

- **Harvested wood may not provide benefits over maintaining natural forest**
  Harvested wood only provides a benefit relative to maintaining a natural forest cover if the rotation period of harvested wood species is shorter than that of natural tree varieties. The rotation period represents how long it takes for trees to reach maturity, and long-rotation species will take longer to absorb the same amount of carbon as short-rotation species.

- **The biogenic carbon system is ill-defined**
  The biogenic carbon stored in timber products is only one element of the biogenic carbon system, which also includes roots and soil.6 These elements are typically considered to be outside of the product LCA boundary, but they have been shown to have an impact on GWP.

Figure 10: Comparison of reference and project systems for accounting for biogenic carbon storage



As a result of the factors, there exists a significant divergence in the approaches to the incorporation of biogenic carbon taken by different standards and guidelines. It is important for practitioners to understand why analyses performed in different contexts may have used different assumptions and/or methodologies. The standards governing calculations of biogenic carbon and their differing approaches are therefore presented in the appendix for more information.

How to model this strategy

While there is no consensus between existing standards, the following approach is recommended. The National Guidelines are based on ISO 21930 and, while this provides a good starting point, it should be complemented with ISO 14067, EN 15804, and EN 16485. The Athena IE4B guidelines provide a useful example of synthesising multiple guidelines, as they combine elements of PAS 2050, ISO 14067 and the WRI GHG Protocol for Products.

Biogenic carbon inflows and outflows should be documented within each module, as recommended by the National Guidelines. For example, the removal of CO_2 from the atmosphere should be accounted in Module A1 and its return to the atmosphere should be reported in Modules A3-A5 (if present in construction waste), B (if disposed/ replaced as part of use-phase maintenance) and C (if maintained until end-of-life). The net flow of CO_2 should be zero unless carbon was converted to methane as part of a combustion process. Although it is not mentioned in the National Guidelines, these flows should be documented separately from all other flows of embodied carbon. EN 15804 specifies how the requirements of ISO 14067 to keep biogenic carbon separate can be applied to each module.

Although some standards do allow for the possibility of permanent storage, such as the Athena IE4B guidelines, this is discouraged. However, ISO 14067 and EN 16485 allow for credits from temporary storage, also known as delayed emissions. These benefits should be calculated based on the methodologies outlined in PAS 2050 (2011) or Ciais et al. (2014) and reported as additional information in Module D. Finally, LCA modelers should follow the requirement in the National Guidelines about the source of wood products from sustainably managed forests. However, it is also appropriate to follow the methodology from Ciais et al. (2014) to determine broader impacts from land-use changes, as outlined in ISO 14067 and EN 16485.

The above represents a very broad overview of how different norms and guidelines interact. A more comprehensive comparison of how different LCA guidelines approach biogenic carbon can be found in the appendix, and additional resources are included in this chapter.

How to perform a comparison with a reference system

The definition of the reference building should include the same considerations as outlined in B3.1 Material sobriety and material selection. Figure 10 compares the stages between the reference and project system when accounting for biogenic carbon.

Equation 4 | Calculation of CO_2 stored in a wood product of density p and volume V

$$\text{Biogenic Carbon } (kgCO_2) = 44/12 \times cf \times (\rho \times V)/(1 + \omega/100)$$

Where **ρ** represents the density of the wood product in kg/m³, **V** represents the volume in m³, **ω** represents the moisture content of the product as a percentage, and **cf** represents the carbon fraction of dry mass (0.5 default). 44/12 represents the ratio of the atomic masses of carbon and carbon dioxide.

Equation from EN 16449: 2014 Wood and wood-based products – Calculation of the biogenic carbon content of wood and conversion to carbon dioxide.

Next steps

This report presents some WBLCA considerations when introducing circular strategies in buildings, since current standards and guidelines do not explicitly address circularity. The lack of clear and systematic guidance on how to account for circular economy in construction should be addressed to ensure a coherent and aligned practice. This document serves as a starting point to bridging circular strategies and WBLCA practically for the construction sector.

Some next steps should include clarifications on circular WBLCA reporting, further evaluation of LCA tools and their integration of circular assessments, as well as examples and lessons learned from applying the concepts laid out in this document. Other circular strategies that, for example, touch on the concept of transfer of ownership could also be explored.

Establishing a coherent industry-wide approach to assessing environmental impacts of building design decisions is key to set achievable and meaningful targets to a more sustainable future.

Appendix

Appendix contents:

Approaches to biogenic carbon

The approaches to biogenic carbon accounting that are put forward in standards and guidelines differ from one another in five major ways. These differences are presented below to a) give practitioners an idea of the different assumptions and methodologies underpinning the analyses they may come across and b) show where the National Guidelines lie relative to other approaches.

1. **-1/+1 vs 0/0 Approaches**
   The National Guidelines have adopted the -1/+1 approach, which involves tracking all biogenic flows during a building's life including uptakes (-1) and releases (+1). Most other guidelines employ this approach, as well. However, it has been criticized because while the net effect should in theory be zero, the calculations may result in negative impacts if the system boundary is not appropriately defined, thereby misleading decision makers. This approach also recognizes that while the new flow of carbon is zero, its GWP may change as sequestered CO_2 is released as methane during combustion. An alterative to -1/+1 is 0/0 (i.e., no accounting for biogenic carbon). This is recommended by the European Commission's Guidance for the development of product environmental footprint category rules (EC2017). This more accurately reflects the aggregated climate impacts with less chance for misrepresentation. Other standards and guidelines such as ISO 14040/44 and EN 15978 also omit any instructions on biogenic carbon and thus implicitly employ the 0/0 approach. There is a third, dynamic, approach that requires a more detailed analysis that is mostly applied in the research field. A dynamic LCA considers the evolution of GWP impacts over time, making it relevant to temporary carbon sequestration and storage in the biomass, while also adding to the complexity of accounting for biogenic carbon and its lack of consensus in the industry.

2. **Reporting requirements**
   The National Guidelines, as well as ISO 21930 and EN 15804, specify that biogenic carbon flows should be documented within each stage and module in which they occur. The National Guidelines also require that biogenic carbon should be included in the total carbon impacts for each stage and module, though the specific contribution of biogenic carbon to this total should be specified. This in contrast with other guidelines which require biogenic carbon to be reported separately from other carbon impacts (ex: EN 15804, ISO 14067, EN 16485, Athena IE4B guidelines, the WRI GHG protocol for products, ILCD, EC2017). More specifically, EN 15804 specifies that biogenic carbon should still be accounted for in the individual modules, while the Athena IE4B guidelines specify that net benefits from biogenic carbon be instead reported in Module D. The other listed guidelines do not indicate how biogenic carbon flows should be reported as long as they are separate from the main results of the analysis.

3. **Credits for temporary carbon storage**
   Several standards provide a credit for temporary storage, and the calculation methods will differ. These standards include ISO 21930 (and thus the National Guidelines), ISO 14067, EN 16485, and PAS 2050. Other standards and guidelines such as EN 15804, Athena IE4B guidelines, FPInnovations wood products Product Category Rules (PCR), and EC2017 do not consider any benefit from temporary storage.

4. **Possibility of permanent carbon storage**
   Several standards include the possibility of permanent biogenic carbon storage. Athena IE4B guidelines, PAS 2050, ILCD, EC2017 allow for the possibility of permanent storage. Storage can be considered permanent after a cut-off period of 100 years, though the starting point of these 100 years also varies depending on the standard. The National Guidelines are aligned with ISO 21930, ISO 14067, EN15804, EN16485, and FPInnovations PCR in that hey do not allow the possibility of permanent storage.

5. **Land-use impacts**
   Several standards and guidelines address some direct impacts of land-use changes by making carbon sequestration contingent on the sustainable management of originating forests (ex: ISO 21930, EN 15804, Athena IE4B), while other documents use an approach based on Ciais (2014) et al. (ISO 14067, EN 16485). PAS 2050 provides default values for select countries. PAS 2050, ISO 14067, EC2017 specify that land-use changes that occurred within a period of 20 years or a full rotation (how long it takes for harvested trees to reach maturity) should be considered.

Table 8. What different standards and guidelines say about biogenic carbon

Standard, Guideline *(influenced by)*	0/0 or +1/-1	Guidelines on permanent and temporary storage	Guidelines on how biogenic carbon should be reported	Guidelines on whether to include land-use change
The National Guidelines ***ISO 21930***	-1/+1	– No permanent storage possible, assumes net zero overall flows. – No specifications relating to benefits from temporary storage.	– No requirement that biogenic carbon be reported separately. – Biogenic flows should be documented within each stage [A-D].	– Negative emission during product phase contingent on forest being sustainably managed.
ISO 21930:2017	-1/+1	– No permanent storage possible, assumes net zero overall flows. – Delayed emissions may be reported as additional information.	– Biogenic carbon (and carbonation) to be aggregated into main indicator. – Biogenic flows should be documented within each stage and module where the flows take place.	– Negative emission during product phase contingent on forest being sustainably managed
ISO 14067 ***Ciais et al.(2014)***	-1/+1	– No permanent storage possible, assumes net zero overall flows. – Impact of carbon storage (>10 years) may be documented separately.	– Emissions and removals from biogenic sources should be documented separately.	– Should take into account land-use changes that occurred within a period of 20 years or a full rotation. Assessed based on Ciais et al. (2014).
EN15804:2012 + A2:2019 ***ISO 14067***	-1/+1	– No permanent storage possible, assumes net zero overall flows. – No credit for temporary storage.	– Biogenic carbon should be documented separately from land-use change and fossil emissions. Biogenic flows should be documented within each stage and module where the flows take place.	– Negative emission during product phase contingent on forest being sustainable managed
EN 16485 (2014) ***PAS 2050*** ***Ciais et al.(2014)***	-1/+1	– No permanent storage possible, assumes net zero overall flows. – Effect of delayed emissions may be calculated based on PAS 2050 (2011) or Ciais et al. (2014) and reported as additional information	– Biogenic carbon should be documented separately.	– Should take into account land-use changes assessed based on Ciais et al. (2014).
Athena IE4B guidelines ***PAS 2050, WRI,*** ***ISO 14067***	-1/+1	– Permanent carbon storage defined as (>100 years). – No credit for temporary storage.	– Biogenic carbon should be documented as part of the Module D.	– Negative emission during product phase contingent on forest regrowing completely.
FPInnovations wood products Product Category Rules (PCR)	-1/+1	– No permanent storage possible, assumes net zero overall flows. – No specifications relating to benefits from temporary storage.	– No specific requirements. Carbon balance may be reported at various stages throughout life cycle. Fossil emissions may be presented as a specific subset.	– Not specified.
PAS 2050	-1/+1	– Permanent carbon storage defined as (>100 years). – Credit may be included but should be included separately. Weighting factor for delayed emissions may be calculated based on linear discounting.	– No requirement that biogenic carbon be reported separately.	– Should take into account land-use changes that occurred within a period of 20 years or a full rotation. Based on default land-use change values for selected countries.
WRI GHG Protocol for products	n/a	– n/a	– Emissions and removals from biogenic sources should be documented separately.	– n/a
ILCD ***PAS 2050***	1/+1	– Delayed emissions beyond 100 years not considered permanent but can be reported separately. – Credit for temporary storage may be included though not recommended as default. Weighting factor for delayed emissions may be calculated based on linear discounting.	– Delayed emissions beyond 100 years included separately as 'Carbon dioxide, biogenic (long term)'	– Not specified
EC (2017a, 2017b) ***PAS 2050*** ***Ciais et al. (2014)***	0/0	– Permanent carbon storage defined as (>100 years). – No credit for temporary carbon storage.	– Biogenic carbon content reported as additional technical information.	– Land-use changes that occurred within a period of 20 years or a full rotation. Assessed based on PAS 2050 or Ciais et al. (2014).
EC (2013b) ***Ciais et al.(2014)***	-1/+1	– No permanent storage. – Credit for temporary carbon storage may be included as additional information	– No requirement that biogenic carbon be reported separately.	– Land-use changes that occurred within a period of 20 years or a full rotation. Assessed based on Ciais et al. (2014)

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