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MASTER THESIS

Sustainability Protocol for University Campuses

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Abstract

The proposed thesis focuses on the importance of applying circular strategies for the management of long-lived, high-use assets in the university sector, where the benefits obtained are greater than the costs; however, the assessment tools lack proper consideration of the aspects of the circular approach, especially regarding long-term durability and replacement cycles. The thesis proposes an extension to the SBTool/ITACA assessment tool to include a new circular aspect specifically designed for the university sector's needs, in the form of a Durability and Replacement Cycles indicator (Durability Ratio) for campus building envelopes. A literature review focused on the SBTool/ITACA and CircularB COST framework for the analysis and allocation of the elements according to SBTool/ITACA enabled the diagnosis of the degree of coverage and the differences among the elements relative to the circular approach interpretation according to the framework, highlighting a key gap in Service Quality, E2: Optimisation & Maintenance. On the basis of the evidence, the result defines the approach's scope, KPI, and reporting boundaries, then formulates an entirely Excel-based approach, which enabled the calculation of the Durability Ratio over a 50-year service life horizon based on the information available in the regulatory Legge 10 documentation used in the SBTool/ITACA assessment approach. The approach was tested on the Digital Revolution House building from the Politecnico di Torino for validity and practical suitability. The results indicate the possibility of formulating a protocol-ready Durability Ratio for campus envelopes, and that durability and replacement cycles can be calculated and reported jointly without overlapping within the SBTool/ITACA assessment approach, using documentation that is already produced for regulatory purposes.

Keywords: Circular economy; Campus sustainability; SBTool/ITACA; Durability Ratio; Durability and Replacement Cycles; Service life; University building envelope; CircularB COST framework; Digital Revolution House (Politecnico di Torino).

Contents

List of Abbreviations

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
ARUP	Arup (engineering consultancy; proper name)
BAMB	Buildings as Material Banks
BIM	Building Information Modeling
BREEAM	Building Research Establishment Environmental Assessment Method
CBMs	Circular Business Models
CDW	Construction and Demolition Waste
CE	Circular Economy
CircularB	COST Action CircularB — Circularity in the Built Environment (CA21103)
CMUR	Circular Material Use Rate
CO	Carbon monoxide (if you intended carbon dioxide, use "CO_2" instead)
CORDIS	Community Research and Development Information Service (EU)
COST	European Cooperation in Science and Technology
CPR	Construction Products Regulation (EU)
CSR	Corporate Social Responsibility
D-Score	Deconstructability Score
DBL	Digital Building Logbook
DfD	Design for Disassembly
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
DIN	Deutsches Institut für Normung (German Standards Institute)
DRH	Digital Revolution House
EAD	European Assessment Document

EC	European Commission
ECA	European Court of Auditors
EEA	European Environment Agency
EMF	Ellen MacArthur Foundation
EN	European Standard (EN standard)
EPD	Environmental Product Declaration
EU	European Union
EU-27	The 27 Member States of the European Union
FAQs	Frequently Asked Questions
GPP	Green Public Procurement
GWP	Global Warming Potential
hEN	Harmonised European Standard (harmonised product standard)
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
INIES	French national database of environmental/health data for construction products ("Base INIES")
ISO	International Organization for Standardization
JRC	Joint Research Centre (European Commission)
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development/Detail (BIM)
MEP	Mechanical, Electrical and Plumbing
Macro-Objective	Level(s) framework "Macro-objective" (EU building sustainability)
PBD	Performance-Based Design

PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
PCRs	Product Category Rules (for EPDs)
RFIs	Requests for Information
SBTool	Sustainable Building Tool (iiSBE)
SC	Subcommittee (e.g., ISO/TC 59/SC 17)
SKPIs	Sustainability Key Performance Indicators
SPEC	Specification
TC	Technical Committee (e.g., ISO/TC 59)
UK	United Kingdom
UKGBC	UK Green Building Council
UNEP	United Nations Environment Programme
WorldGBC	World Green Building Council
WRAP	Waste & Resources Action Programme
BSI	British Standards Institution
CAM	Criteri Ambientali Minimi
CEN	European Committee for Standardization
IDP	Integrated Design Process
ITC-CNR	Istituto per le Tecnologie della Costruzione – Consiglio Nazionale delle Ricerche
NGO	Non-Governmental Organization
PdR	Prassi di Riferimento
SB	Sustainable Building
SBRSs	Sustainable Building Rating Systems
SBToolCZ	SBTool—Czech adaptation
SBToolPT	SBTool—Portuguese adaptation

SBToolPT-H	SBToolPT—Habitação (Housing) module
UNI-PdR	UNI—Prassi di Riferimento
WBLCA	Whole-Building Life-Cycle Assessment

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Chapter 1. Introduction

1.1 Background

The growing forces of climate change have increasingly transformed the way resource consumption and the production of articles occur in society (Menegaki & Damigos, 2018; UNEP, 2021). Within the context of, and resulting from, these changes in the manner in which resources are consumed and articles are produced, the construction industry has remained one of the heavyweight sectors contributing to environmental concerns: the built environment is among the largest material users globally (non-metallic minerals > 50% of total material use) and produces about 0.74 kg of municipal solid waste per person per day globally (Kaza et al., 2018). In addition, the EU's high CDW 'recovery' rate (~89%) often hides downcycling and "poor levels of circularity" (JRC, 2024). Globally, circularity remains low—about 8.6% in 2022 and about 7.2% in 2023—indicating substantial untapped potential for material value retention (Circle Economy, 2022; Circle Economy, 2024). At the same time, the construction industry consumes about 36% of final energy and accounts for about 37% of energy-related CO_2 emissions globally (UNEP, 2021). These forces define construction work and new construction performance indicators in terms of circular construction works and processes, with the broad vision of sustainability encompassed in the principles of environment, society, and economy (Vogt & Weber, 2019).

From linear to circular, the circular economy (CE) has been proposed as a real-world application to render construction activities genuinely sustainable (Geissdoerfer et al., 2017). CE reinterprets the take–make–dispose paradigm in terms of slow, close, and narrow resource cycles via methods such as long-life design, maintenance, repair, reuse, remanufacture, and recycling, applied at macro (countries/regions), meso (eco-industrial parks), and micro (products, enterprises, users) levels, as articulated in Kirchherr et al. (2017) and further explained in Geissdoerfer et al. (2017). The industry-specific implementation of CE—en vogue via the Ellen MacArthur Foundation—translates these into construction requirements to reduce footprints and waste while protecting construction activities from market volatility in construction materials (Nobre & Tavares, 2021; Akhimien et al., 2021).

1.2 Problem Statement

Despite growing policy support, the integration of circular-economy principles into mainstream building sustainability schemes remains selective and fragmented—particularly with respect to long-term durability, service life and replacement cycles of building components. While current frameworks increasingly address energy, operational carbon and, to some extent, end-of-life management, they still tend to treat component longevity implicitly, without dedicated indicators that link replacement cycles to circular-resource strategies and whole-life performance (Kouka et al., 2024).

Even in the case of the common reporting framework in the EU, namely Level(s), there appear to be areas of missing or loosely defined indicators and thresholds, together with discrepancies between indicators and standards that limit the monitoring of circular-economy data quality and the comparability of results (Rastegari, 2025). As a consequence, durability-related aspects—such as service-life assumptions, replacement frequencies and maintenance regimes—are only partially operationalized within current tools.

From a usability perspective, end-user requirements also remain poorly addressed. The tools and databases available to perform life-cycle assessment are frequently misaligned with practitioners' needs, both in terms of interface design and in the level of support they provide for interpreting and applying circular-economy metrics, including those implicitly related to service life and replacement cycles (De Wolf, Cordella, Dodd, Byers, & Donatello, 2023).

This partial alignment has real-world implications. The absence of targeted, threshold-based circular key performance indicators (c-KPIs) that explicitly integrate durability and replacement cycles makes circular strategies difficult to compare and translate into design decisions across projects, weakening performance assessment and benchmarking (Rastegari et al., 2025). At an outcome level, "high" construction and demolition waste (CDW) "recapture" rates in Europe have often reflected low-value routes (downcycling) rather than genuinely circular strategies that extend service life, minimise premature replacement and prioritise high-value recovery (European Commission Joint Research Centre [JRC], 2023). Globally, circular-economy progress has stalled at around 7.2%, and the risk of "circular-washing" is likely to increase if definitional schemes and evaluation tools continue to lack robust, operational indicators for durability and long-term component performance (Circle Economy, 2024).

1.3 Objectives

Campuses are key stakeholders in the transformation for sustainability. Campuses consolidate high concentrations of diverse building assets characterized by high occupancy levels over the year; they manage long-lived assets influencing energy, materials, and operational costs over the long term; and—crucial to the point—they are 'living labs' where operations, learning, and research are mutually reinforcing. A campus metric capable of providing circular performance, therefore, wields disproportionate influence; it could directly affect asset management decisions and shape the 'whole' urban landscape for the better.

In this context, the thesis bears a single strategic objective: enriching the SBTool/ITACA approach for university campus evaluations in the context of implementing an enhancement based on the circular-economy approach, one which should be evidence-based, implementable, and useful for decision-making purposes. Originally, the thesis does not set an assumption about the approach; instead, the literature analysis' match with the SBTool/ITACA approach for the university campus makes the most suitable approach appear in the context. In this approach, the result reveals Durability & Replacement-Cycle as the most material aspect based on the operational feasibility of the D-Score setting.

Consequently, the goals are dual in nature. Firstly, to formally establish Durability & Replacement-Cycle as a criterion eligible for the protocols—not only specifying the focal point of the criterion, key performance indicator, and reporting framework, but also establishing the exact location within the SBTool/ITACA framework without having the score double-counted and affecting the consistency of other credits. Second, to demonstrate the relevance of the criterion by implementing and validating the process within the Politecnico di Torino campus setting for the Digital Revolution House (DRH), interpreting the outcome not only from the numerical perspective, but also from the point of informing decisions at the Politecnico di Torino campus.

The goal would be an exact, replicable, and reportable circular-economy indicator, which could be provided together with existing results for SBTool/ITACA, thus providing a measure of circular-economy performance in the same context where decisions are made, namely at the university campus level. In doing so, the purposes are tied together for their rigor and utility in academia and practice, starting from the realm of research, accessible for a practical and applicable context within the university setting, and ready to serve the endeavour for a sustainable university campus.

1.4 Research Questions

The promise of the circular economy (CE) could reduce resource consumption, allow for materials of higher value to be recovered at the end-of-life stage, and enhance long-term building performance. Campus settings are especially relevant to be addressed in this context, where the management of various resources over extended periods and the transfer of knowledge within the operational phase for the generation of guidelines could be suitably achieved. However, within the framework of existing protocols for sustainability assessment, such as SBTool/ITACA, the use of CE features is still in a nascent stage, and thus the primary deficiency in CE will be identified from an evidence-based analysis of CE and the existing body of sustainability indicators and then used as a protocol-ready criterion for the Politecnico di Torino campus.

The main question of this research is:

- In what ways might SBTool/ITACA be improved for campuses to be made more sustainable through the incorporation of a clear CE criterion?

In detail, this study addresses the following questions:

Q1 – What are the CE gaps seen in SBTool/ITACA regarding the mapping of literature-defined indicators for the purposes of campus implementation?

Q2 – Which of the extracted gaps represents the most obvious and practically possible primary gap for the school setting?

Q3 – In what manner should the key gap be identified, and where should it be placed within SBTool/ITACA?

Q4 – How might the key gap be tested & validated on the Politecnico di Torino campus at the Digital Revolution House?

Q5 – In what manner are the effects of consideration of the CE criterion on assessment results on campus?

Q6 – Does the incorporation of CE tenets within the planning of the campus, as highlighted through the additional criterion, ensure a sustainable campus?

To address these issues, the thesis intends to offer a broader basis for the assessment of campus sustainability, recognizes the lack at the protocol level, defines the identified lack as an authentic indicator, and proves the relevance of the proposed approach on an existing building on a campus. The next chapter bears the description of the circular economy notions applicable to the building sector, the SBTool/ITACA framework, the CircularB COST classification used within the indicators, and the adaptability guidelines for the proposed integration.

1.5 Thesis Structure

From context to application, this thesis proceeds directly and purposefully. From context, the thesis locates the research within the broader context of the circular economy (CE) and the role of university campuses as long-lived, high-use assets. Against this backdrop, the existing protocols for sustainability assessment, SBTool/ITACA, are explained for context on the necessity of an enhancement at the level of the protocol.

The research then builds the evidence base. A focused review identifies the CE and sustainable development indicators from the literature and organizes the results according to an open classification logic adapted for the campus context. Based on this framework, the indicators are matched to SBTool/ITACA to identify zones of full coverage, partial coverage, and discrepancies. Notably, the key CE discontinuity is not predetermined; it follows from this process.

Therefore, the thesis formalizes the gap identified in the thesis as a protocol-ready criterion. The indicator 'Durability & Replacement-Cycle' is specified within the context of scope and KPIs for reporting, to avoid circularity and inclusion within the SBTool/ITACA framework, such that circularity becomes visible and measurable among the existing credits.

The latter portion of the thesis applies and tests its validity at the Politecnico di Torino campus at large. With the Digital Revolution House (DRH) building as the case study, the indicator measure is used, and the results are presented at the level of the building elements and the building, with consideration of robustness carried out by sensitivity analysis.

The thesis ends by summarizing contributions, acknowledging limits of methods and data, and discussing possible avenues for development in the future (such as implementation at the university level and integration into the continuously changing European requirements).

Appendices contain the complete mapping tables, the indicator codebook, computation fields, and other information.

A graph on the below shows the flow of the thesis.

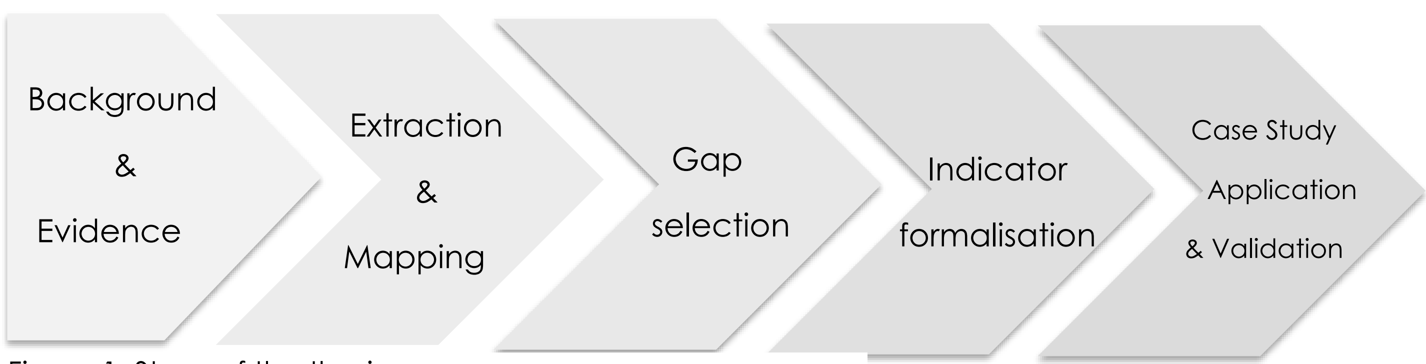


Figure 1. Steps of the thesis

Chapter 2. Circular Economy in the Built Environment & Assessment Protocols

2.1 Circular vs. Linear Economy; 10R

Expanding on more traditional criticisms of the open-ended linear economy, in which natural resources were classified as input sinks and waste sinks (Pearce & Turner, 1989; Boulding, 1966), and, in turn, associated with high resource flow, emission, and leakage levels, the "take–make–waste" paradigm has come to be known in more modern parlance. These criticisms, in turn, serve to support our own usage of what has come to be known as the "circular economy" paradigm, in terms of "a regenerative, closed-loop approach in which materials, products, and services are designed, produced, and distributed in ways that reduce their waste, leakage, flows, and consumption of resources and energy, and environmental impacts" (Geissdoerfer et al., 2017), with activities in terms of design-for-long-life, maintenance, "repair, reuse, remanufacturing, refurbishing, and ultimately, product recovery" (Bocken et al., 2016), with activities in terms of the frequently mentioned 9R/10R "value-retention hierarchies" (Reike et al., 2018; Potting et al., 2017), in terms of refusal/rethink, product-level reuse, [and] product-level repairs, in descending priority, followed by "material-level recovery, such as recycling, and then energy recovery."

One of the most-quoted syntheses defines CE in the following manner (Kirchherr et al., 2017, p. 224):

"We have defined CE in our iterative coded model as an economic system in which the 'end-of-life' paradigm is replaced with 'reducing, alternatively reusing, recycling, and recovering' materials in production/distribution and consumption activities. This occurs at both micro level (products, firms, and consumers) and macro level (city, region, nation, and beyond) with the objective to achieve sustainable development, thus simultaneously establishing 'environmental quality, economic prosperity, and social equity' for [the] benefit of 'generations to come,' made possible by new models of consumption and production."

From Linear to Circular.

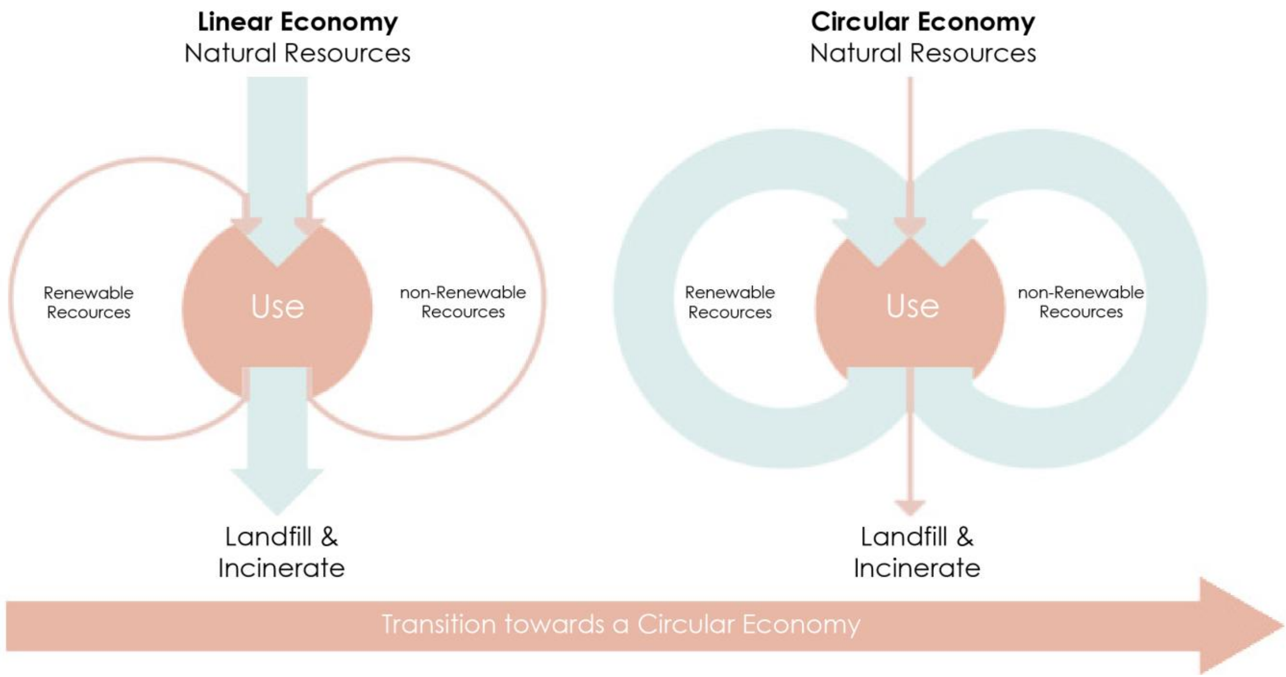


Figure 2. From a linear to a circular economy. Adapted from PBL Netherlands Environmental Assessment Agency (2016).

The 10R value-retention hierarchy.

There are different ways of achieving the goal of reducing consumption of natural resources and materials, with the objective of ensuring minimal waste. These options must be prioritized in line with their level of circular economy (Potting et al., 2017). "Smarter product use and production" (using product sharing) ranks higher in priority compared to "extending product life," followed by "useful application of materials" achieved through recycling or energy recovery. "The higher the level of circular economy, the more environmental benefits" (as highlighted in Potting et al., 2017), with materials being retained in the chain and reused with minimal loss in their quality, thus preventing primary resource consumption. There can be exceptions, such as chemical recycling of contaminated plastics (back-to-monomer process) due to high energy consumption (as indicated in Potting et al., 2017), or an increment in usage due to access strategies (like car sharing).

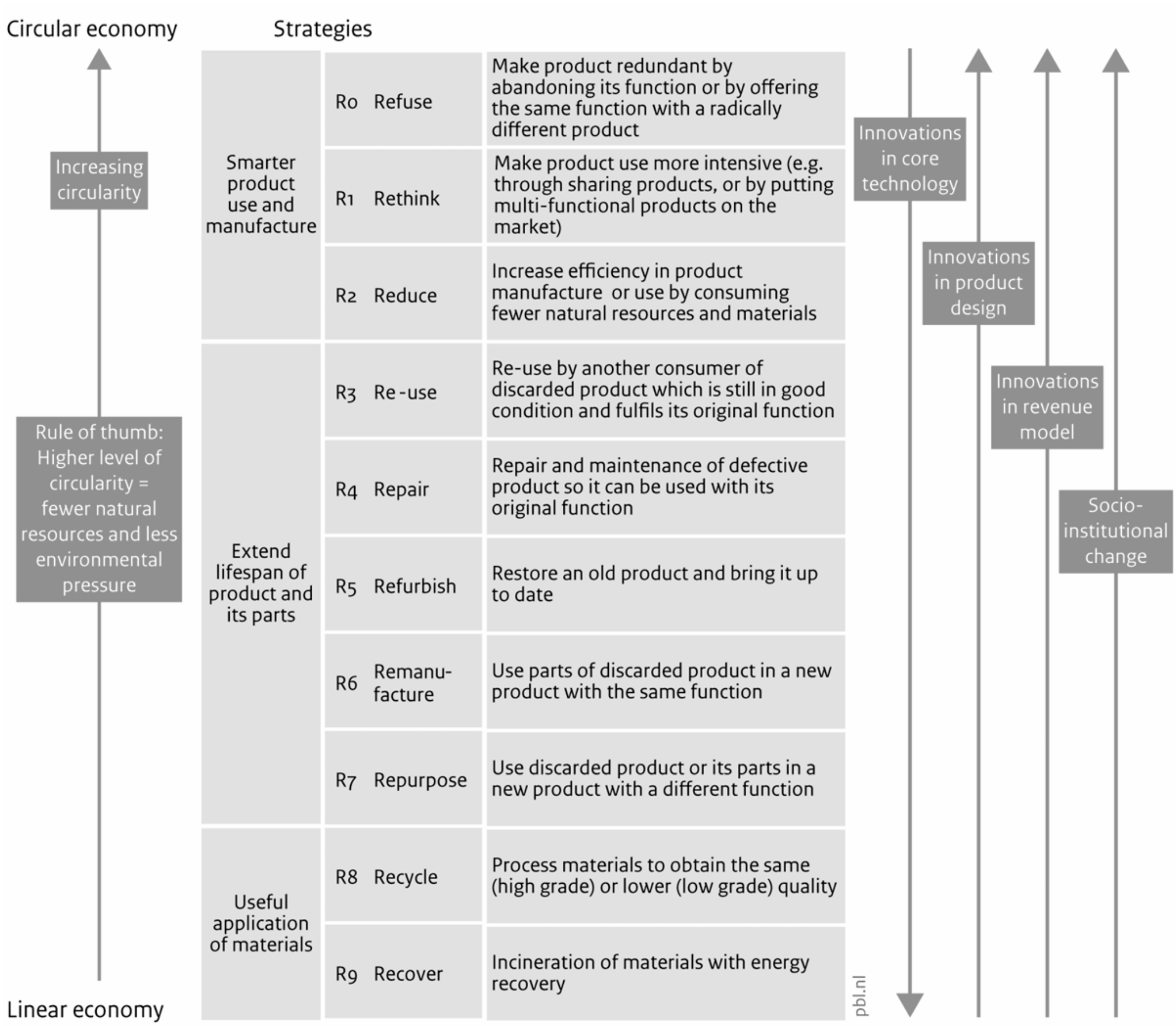


Figure 3. Circularity strategies along the production chain, according to priority (10R). From Potting, Hekkert, Worrell, & Hanemaaijer (2017), PBL Report 2544.

2.2 CE Strategies in Architecture (DfD, Adaptability, Passports)

For this thesis, Design for Disassembly (DfD), adaptability, and passports will be incorporated as the primary tools of a circular economy because they address the points of highest leverage in the life cycle of buildings: Design for Disassembly makes high-quality disassembles possible through reversible assemblies; adaptability gives buildings longer lifetimes through anticipation of change and avoidance of premature disassembly; and passports create the enabling data intermediary to support the tracing and interoperation necessary to facilitate reuse, procurement, and conformity with regulations to close material cycles.

2.2.1 Design for Disassembly and Adaptability (DfD/A): scope, intent, and use

A method of designing a product or an infrastructure with the intention of finding it easy to disassemble at the end of the product life span with the purpose of reuse, recyclable materials, or using them to produce fuel or whatever form of waste diversion there is. (ISO, 2020); (ISO, 2016).

ISO 20887:2020 — Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements, and guidance — gives a general idea of DfD/A principles as well as methods of implementing those principles during the design phase. This international ISO standard is meant to benefit owners, architects, engineers, product designers, product manufacturers, as well as individuals involved in the financial, administrative, construction, modification, deconstruction, or demolition phases of construction works. ISO standards offer various benefits to help increase sustainability and reduce time and costs that can be spent during the entire lifetime of buildings (ISO, 2020).

It is applicable to any types of buildings (commercial, industrial, institutional, residential), as well as civil engineering works (e.g., dams, bridges, roads, railways, runways, utility systems, pipelines) and components of these. It is relevant in new works, renovation, refurbishment, as well as improvement of buildings, systems, civil engineering works, and components. It is most beneficial if DfD/A is taken into consideration in a project from a very early stage to derive benefits not only in renovation, refurbishment, reuse, recycling, and disposing of works at the end of use (ISO, 2020). Relation to other ISO documents. ISO 20887 is meant to be used in conjunction with ISO 15392 (general principles) as well as the ISO 15686 series (service life). This document gives guidelines on how performance can be evaluated across various DfD/A principles, making it clear that no specific performance levels are established in the document, only requirements that shall be mandatory in implementing DfD/A principles (ISO, 2020; ISO, 2019; ISO, 2011).

This international standard is a product of ISO/TC 59/SC 17 (Sustainability in buildings and civil engineering works) (ISO, 2020).

2.2.2 Disassembly: principles, practices, and safety (what to design for)

In design for disassembly and adaptability (DfD/A), disassembly is focused on assemblies that can be disassembled at the point of end-of-use (and during renovation) in a way that components are either recovered, reused, recycled, or disposed of in a way that diverts them from waste. This is addressed by ISO 20887:2020, whose standards cover the principles of integrating disassembly in design in respect of building construction works and civil engineering works (ISO, 2020).

Core principles (ISO 20887 §5.3): There are seven factors to be considered during the design process. These factors include accessibility to components and/or services; independence (where possible, minimize interdependence to facilitate selective disassembles); avoidance of unnecessary treatment/finish; support for reuse (circular economy business models); simplicity; standardization; [and] disassemblability or disassembly safety (ISO, 2020).

Functional supports: ISO extends these standards with specifics of what this entails in practice: use components that can be readily removed, removed safely, removed cost-effectively, and transported safely; make provision in components for handling (e.g., lifting points or temporary supports); size components for intended handling across assembly, disassembly, transport, reprocessing, and subsequent assembly; provide spare parts and on-site storage for custom parts to enable easy replacement and minor alterations (ISO, 2020).

Safety and documentation: Disassembly safety is of utmost importance. ISO requires a disassembly strategy considered from project inception and revisited at execution in view of imprecise as-builts, wear and damage, hazardous wastes, changing regulations, weather, and errors/omissions. Secure disassembly relies on accurate information about original materials/assembly methods and subsequent major renovations to support the correct disassembly sequencing for reuse and recycling. Documentation supporting safe disassembly shall be maintained and available throughout the life of the works. Features that support safer disassembly include accessibility, exposed connections, reversible connections, interdependence (manageable loads), avoidance of unnecessary finishes, simplicity, standardisation, and durability (ISO, 2020).

When to integrate: Benefits are maximized when DfD/A is considered very early in a project, with the aims of facilitating repair, refurbishment, reuse, recycling, and appropriate disposal at end of use (ISO, 2020).

State of practice (scoping review): DfD has various definitions and implementations; 50% of built DfD structures reported have area < 300 m^2; 75% use timber structures, while the research literature on enabling technology is dominated by connections for reinforced concrete and hybrid concrete–steel structures. DfD in AEC is a relatively young field that is rising in popularity due to waste-minimisation policies and CE transitions; growth has been slow as a disruptive approach in a conservative industry, but research and application are increasing. A broad, qualitative overview of the whole DfD domain had been lacking; detailed guidelines exemplified with real solutions are required before adoption can scale (Ostapska et al., 2024).

Complementary topic-specific reviews include deconstruction potential (Carvalho Machado et al., 2018), design process (Kanters, 2018), design strategies (Eberhardt & Birkved, 2019), BIM's role in deconstruction (Akbarieh et al., 2020), DfD critical success factors (Akinade et al., 2017), and reusability/recyclability factors (Akanbi et al., 2018).

2.2.3 Adaptability in the Built Environment (versatility, convertibility, expandability) and how it is measured

In the construction industry, design for disassembly and adaptability (DfD/A) is formalized in ISO 20887:2020, which contains principles, requirements, and recommendations that help in ease of modification during the future phases of a product's life cycle to recover components at the end of use (ISO, 2020).

Rationale & types: Adaptability is necessary to accommodate changes in use type, demographics, user needs, or adaptation to external factors (e.g., climate change) for resilience/futureproofing; initial cost may be balanced against future adaptation cost. Adaptability comprises specific (known/expected) and general (unknown potential future) adaptations, and can be sequential (over time, often non-reversible) or parallel (various functions, repeatable). Accounting for universal design at the outset can avoid costly later conversion (ISO, 2020).

Principles to consider (ISO 20887):

Versatility — ability to accommodate different functions with minor changes to the system; focuses on minimizing strip-out/fit-out over building life cycle (such as folding partitions, components that are interchangeable, multi-functional spaces) (ISO, 2020). Convertibility — ability to easily accommodate large changes through modifications (usually non-structural) to fit-out of interior spaces/systems; related to versatility but focuses on infrequent or future changes (such as office to residential use) - will include long span, post and beam structure, flexible base/shell structure allowing easy infill, ability to handle heavier loads (ISO, 2020).

Expandability — ability to easily accommodate additions through vertical or horizontal expansion of spaces, facilities, capacities - entails allowing for foundation/superstructure modifications to support heavier loads as well as designs that make it easy to disassemble walls/envelopments/partition walls without damaging materials so that materials can be reused either off or on-site (ISO, 2020).

How adaptability is evidenced and scored today (Level(s) 2.3): At EU level, within Level(s), Indicator 2.3 ("Design for adaptability and renovation") explains why adaptability matters (extend service life, avoid early obsolescence), what is measured (design aspects that facilitate future adaptability), and how/when to measure: at Level 1 (concept design), Level 2 (detailed design & construction), and Level 3 (as-built & in-use). In L1 a checklist is used; in L2/L3, "multiply the score obtained for each design aspect by the weighting factor and then sum up the resulting weighted scores to obtain a score out of 100" (Dodd, Donatello, & Cordella, 2021; European Commission, 2024).

2.2.4 Materials/Building Passports (definition, fields, BIM link)

Materials passports are (digital) sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse (Buildings as Material Banks [BAMB], 2018; BAMB, 2019). The intent is a "one-stop shop" solution supported by a platform that enables the generation of passports and access to them in circular use (BAMB, 2018; Community Research and Development Information Service [CORDIS], 2022).

Data needs & templates: Recent European work on data requirements for material/digital product passports identifies core fields such as composition and quantity of materials, location in the asset, type of connection, disassembly instructions, condition history, and origin; and proposes structured templates that can be integrated with BIM workflows for maintenance, renovation, and demolition phases (Çetin et al., 2023).

Building-level repositories and logbooks: The EU Digital Building Logbook initiative situates building/material passports within broader data repositories that address siloed information via shared storage and access—providing consistent, long-lived records for assets (European Commission, 2024).

Practice recommendations: Guidance to accelerate reuse via passports emphasizes: (1) whole-building reuse where feasible; (2) pre-redevelopment audits; (3) prioritizing deconstruction over demolition; (4) a deconstruction strategy; (5) passport frameworks interoperable across platforms; (6) databases segmented by building lifetime (existing, proposed, completed); (7) using recovered materials in new projects; and (8) supportive regulation valuing materials' economic, social, and environmental attributes (BAMB, 2019; UK Green Building Council [UKGBC], 2024; Metabolic, n.d.).

A passport is only useful if a structured set of data is available and maintained over time in each project; BAMB ties these data to characteristics that enable reuse, and sector templates demonstrate how BIM can store composition, location, relations, disassembly operations, condition, and origin (BAMB, 2018; Çetin et al., 2023).

2.2.5 Why these three together (DfD, adaptability, passports)

In the 10R "value-retention" hierarchy, strategies that slow/close/narrow loops at the product/component level (e.g., reuse, restore, refurbish, remanufacture) generally deliver greater environmental benefits than material-level options (recycling) or energy recovery (Potting et al., 2017). DfD enables high-value recovery as a technical process; adaptability prevents early obsolescence; passports ensure recovery is discoverable (Potting et al., 2017)

Level(s) offers a common EU language to evidence adaptability performance (Indicator 2.3), yet market assessments still point to limited scope/uptake—highlighting the importance of criterion-based language inside assessment protocols to make circular performance visible (Dodd et al., 2021; European Commission, 2024).

2.3 Barriers to CE Implementation

To structure the evidence related to circular construction, barriers have been categorized according to six interlocking layers that reflect the chain. This categorization prevents duplication and allows the reader to navigate easily between "what we measure," "how we compute it," "how it is purchased," "what the law allows," "what can be built and moved," to finally "who knows how to do it." The next subsections summarize the evidence related to each of the layers.

2.3.1 Measurement & indicator gaps (standards, KPIs, thresholds)

Recent results highlight indicator immaturity, as well as monitoring gaps that hinder the adoption of circular economy (CE) in the built environment. A review of the EU Level(s) framework in 2025 identifies a lack of scientific literature, missing metrics, undefined thresholds, as well as discrepancies with referenced standards/regulations in several KPIs, making these KPIs not comparable (Rastegari, 2025). As highlighted in the analysis, issues are identified in KPIs such as 1.2 Life-cycle GWP (both missing thresholds & alignment), a range of indicators under Macro-Objective 2 (e.g., 2.1 Bill of quantities, materials, and lifespans, missing thresholds & alignment; 2.4 Design for deconstruction, reuse, and recycling, missing metrics, thresholds & alignment), some indicators of Macro-Objective 4 (e.g., 4.3 Lighting & visual comfort & 4.4 Acoustics & protection against noise, missing thresholds & alignment), as well as in a range of indicators of Macro-Objectives 5 & 6, where indicators are missing metrics/thresholds & display misaligned indicators (Rastegari et al., 2025). A flexible process that allows various methods for a set of indicators can also lead to differences in results of analysis, thus limiting inter-project comparability (Rastegari et al., 2025).

Table 1. Level(s) KPI weaknesses—missing metrics, undefined thresholds, and (mis)alignment with standards/regulations. Source: compiled from Rastegari (2025).

Macro-Objective	Indicator	Metrics Definitions	Threshold Definitions	Alignment with Standards/Regulations*
1. Greenhouse gas and air pollutant emissions along a building's life cycle	1.1. Use stage energy performance	✓	✓	✓
	1.2. Life cycle GWP	✓	✗	✗
2. Resource-efficient and circular materials life cycles	2.1. Bill of quantities, materials, and lifespans	✓	✗	✗
	2.2. Construction and demolition waste and materials	✓	✓	✗
	2.3. Design for adaptability and renovation	✓	✓	✗
	2.4. Design for deconstruction, reuse, and recycling	✗	✗	✗
3. Efficient use of water resources	3.1. Use stage water consumption	✓	✓	✓
4. Healthy and comfortable spaces	4.1. Indoor air quality	✓	✓	✓
	4.2. Time outside of thermal comfort range	✓	✓	✓
	4.3. Lighting and visual comfort	✓	✗	✗
	4.4. Acoustics and protection against noise	✓	✗	✗
5. Adaption and resilience to climate change	5.1. Protection of occupier health and thermal comfort	✗	✓	✗
	5.2. Increased risk of extreme weather events	✗	✗	✗
	5.3. Increased risk of flood events	✓	✗	✗
6. Optimized life cycle cost and value	6.1. Life cycle cost	✓	✗	✗
	6.2. Value creation and risk exposure	✓	✗	✗

At the systems level, the EU monitoring indicates that circularity progress is only moderate. This is because the EU material footprint in 2023 stood at 14.1 t/cap, with waste generation at approximately 5 t/cap in 2022, both of which are high in absolute terms. (EEA.2024). Whereas resource productivity has been increasing (approximately €2.1/kg of materials in 2022), the material footprint is essentially flat, suggesting that circularity has not yet taken off. Recycling rates are high, but the circular material use rate (CMUR) is essentially flat around ~11.5% since 2016, indicating that the use of materials in the form of recyclables and aggregate use alike has been essentially stable. In this respect, material stock in use in the EU continues to cumulate at a rate of ~+2.6%/year, indicating that waste generation is a long way behind resource use. Without large mineral waste, landfilling is essentially reduced to a level of around ~306 kg/cap, with the EU recycling nearly half of the waste generated, yet only recycling is not sufficient, with a reduction in particular material use as well as a development of a functional secondary market called for (EEA, 2024).

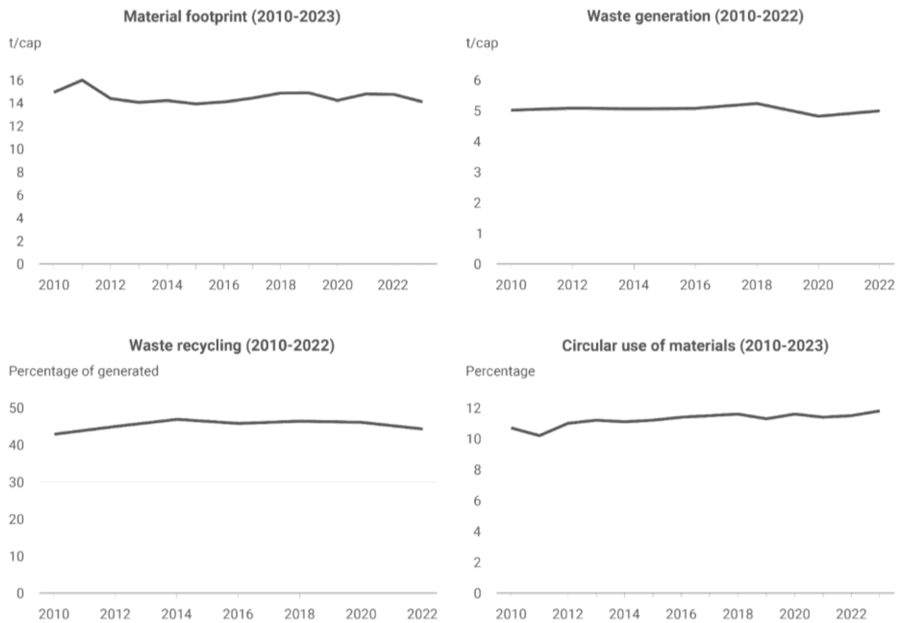


Figure 4. EU resource and circularity indicators. Source: European Environment Agency, Sustainable Resource Management in the EU dashboard (EEA, 2024).

Taken cumulatively, these results mean that (i) immaturity and misalignment in indicators are barriers to project-level measurement and decision-making,while (ii) results of macro-level circularity outcomes are unaffected by enhancement in waste management performance—both of which emphasize the importance of well-defined, thresholded, and standards-compliant KPIs that could catalyze effective CE in building assessment protocols (Rastegari et al., 2025; EEA, 2024; ECA, 2023; . (n.d.). Indicators for Circular Construction - Publications).

2.3.2. Tools, data & workflow integration (BIM–LCA–Level(s))

The mainstream integration of LCA within the context of buildings is hampered by the intrinsic high complexity of buildings as well as LCA itself (Guinée, 2002; Lasvaux et al., 2015; Malmqvist et al., 2011; Pomponi et al., 2018). Professionals lack overall information on tools and data available within their region (Francart et al., 2019). Data obtained through interviews and focus groups reflect demands for examples and best practices, easy information exchange, increased integration with BIM, and simplified guidance. At the same time, there is a perceived overabundance of tools not meeting demands or not easily implementable (Cambier et al., 2020; Ariyaratne & Moncaster, 2014). International initiatives support increased mainstreaming (WorldGBC & Ramboll, 2019); there is harmonised methodology, processes, tools, examples of cases, and databases. Survey results have identified non-incentivizing and poor data availability as primary hindrances (IEA, 2021; Rasmussen et al., 2020). Systematic reviews support the infancy status of LCA studies related to buildings. A harmonized collection of demands on requirements, methodology, and data is proposed (Sauer & Calmon, 2020). Intercomparison of EPD methods concludes there is a need to develop harmonized tools for categories of impact and assessment methods/indicators, boundaries and service lives of products and inventory. Scenarios of assessment and data inventories must be harmonized (Passer et al., 2015).

The Tools & Data Landscape for Practice:

A non-exhaustive presentation of LCA software and databases offered in the EU identifies three key user-driven qualities in LCA software tools: (i) comprehensiveness (specifications and focus on the construction sector, system boundaries, indicators, level of modelling detail), (ii) robustness (conformity to standards, data quality and transparency), and (iii) operationality (ease of accessibility, data transfer or interoperability between tools, costs and training support needed); the current market fails to provide enough support to mainstream LCA (De Wolf et al., 2023).

Integration of BIM and LCA:

Indeed, BIM/parametric LCA literature discussion highlights data entry method (BIM vs. parametric LCA), modelling stage/LOD parameter, software tools, parameters measured, functional unit, and lifecycle phases (Cavalliere et al., 2019). Past evidence representing the slower adoption rate in BIM is related to interoperability between tools and systems within the construction industry, change to processes, legal matters, and training and employment (Arayici et al., 2011; Walasek & Barszcz, 2017). These remain current conditions within the industry against which integrating BIM and LCA could be challenged. The industry studies have indicated that their users appreciate graphical user interfaces, easy data visualisation and understanding, with automation of analysing tasks such as design option assessment, with flexibility (Zimmermann et al., 2021; Potrč Obrecht et al., 2020). The high adoption rate of BIM in certain countries indicates imminent potential for quicker integration (IEA, 2021).

Differences among tools and among databases:

Comparison analyses have demonstrated that software/database choices have a strong influence on results. For the same building, plug-in/database variations showed ≈22% variation in material effects depending on database contents and customisation (Dalla Mora et al., 2019). Cross-platform comparison studies conducted on two buildings in Finland showed >15% result variations at the whole-building level and >40% at the material level among programs (Emami et al., 2019). Cross-validation between databases (e.g., Ecoinvent and INIES) indicated non-negligible result variations and suggested the use of combined LCA/service-life datasets to validate assumptions (Hallouin et al., 2014). Cross-regional comparison tests indicated regional result variations across life-cycle phases (Frischknecht et al., 2020). For certification purposes, envelope analyses have indicated that EPDs could have inadequate minimum scopes or could underestimate spatial variations for the EPD framework at product and beyond (Del Rosario et al., 2021). Previous studies at multiple databases indicated >100% variations between EPD and generic results for individual indicators and support improved usage of generic to product- and country-based datasets (Lasvaux et al., 2015).

How to appraise tools (criteria in the literature):

Past assessment metrics included data size/quality, impact method coverage, graphical display, sensitivity analyses, costs, support services, transparency, availability for demos, and data credibility (Rice et al., 1997; Hollerud et al., 2017). A framework to develop tools for environmental assessment is categorized according to themes/issues/parameters (Energy & pollution; materials & waste; IEQ & health; water; site & ecology; management) with no direct assessment of methods to ensure transparency or accessibility/usability from the assessment end (Wallhagen et al., 2013). A scan on current tools for the cement industry included ISO 14040 compliance, usage of database tools, data quality assessment, and methodological choice, with very little attention to usability, method coverage, or conformity with European standards (Olagunju & Olanrewaju, 2020). A combined checklist highlights adherence to standards, usage of Building Information Modeling (BIM) tools, interaction, credibility, and understanding (De Wolf et al., 2023).

Interoperability and digital EPDs:

As the establishment of LCA is reliant upon quantities in BIM, data exchange and interoperability crucially involve EPD contents and external databases. Typology varies according to whether the software couples and transfers both LCA and design data, or only design data, or only LCA data, or no data at all, with variations like conversion of units and independence of software (De Wolf et al., 2023). As one moves to the standards level, the structure of data templates is established in EN ISO 23387 and data in dictionaries is determined in accordance with EN ISO 23386. ISO 22057 describes EPD data templates to be employed in data transfer in accordance with BIM; its environmental part is taken from standards such as EN 15804 and ISO 21930 and pertinent PCRs (ISO, 2022). As per existing scientific literature, there are limitations to computer interpretation of EPDs—particularly with respect to scenario descriptions and the unique machine-readable identification of products and their performance in EPDs—creating a roadblock in their direct translation to LCA/BIM (Aragón et al., 2024).

Implication for practice:

The results show that there is a demand to ensure aligned and harmonized content (following standards with consistent methods and verified data), functional pipelines (transparent and automatable data flows between EPDs and LCA databases/BIM), and supportive tools (accessible guidance and training/support as well as affordable costs) to allow simplified workflows (De Wolf et al., 2023; Cavalliere et al., 2019; Dalla Mora et al., 2019; Emami et al., 2019; Hallouin et al., 2014; Frischknecht et al., 2020; Del Rosario et al., 2021; Lasvaux et al., 2015; Rasmussen et al., 2020).

2.3.3 Regulatory, liability & safety (codes, warranty, fire)

A classification of barriers to reuse proposed in the literature related to reuse subject to fire safety constraints is given in Table 2. This classification divides the barriers to reuse identified in the literature

Technical: deconstructability (ease of removal of the product), and product/material related questions such as aging or material type - single versus combined.

Economic: increased cost of second-hand goods over new goods. The cost of storing and distributing second-hand goods.

Organizational: Lack of information during installation; Ensuring reconstruction is done safely; Unfavourable or unclear market demand; Challenges in ensuring coordination across disciplines; Increasing uncertainty during projects; Limited time to garner information and procure second-hand items; Lack of storage space; Regulations that discourage second-hand products; Warranty and/or insurance of products; Ensuring certification when there is no reuse criteria; Unfavourable information on product history and product information.

Code context and typical obstructions.

Swedish building regulations place a considerable role with regard to the owner of buildings and at the same time provide flexibility in designing buildings with the option of recycled products. As a consequence of the harmonization process with the EU, there have been adjustments in the classification standards related to fire classifications that have been changed to either the European or kept at the national level; there have been new classifications (for cables) and a tougher standard (for smoke-tightness of stairwell door S200, introduced in 2011) (McNamee et al., 2023). This means that if the door had not been tested for S200 standards prior to 2011, it is no longer fit to be used in a stairwell door but could still qualify to be used elsewhere if it is possible to determine its standards.

Fire performance characteristics of recycled materials.

Re-use eligibility relies on establishing fire performance data relevant to the demand. This can be achieved in one of two ways: (i) resorting to existing data where valid (considering the material's age, existing conditions, and history of use), or (ii) assessment. Prescriptive methods can be employed if there is proof that existing classification is compliant or superior to current demands. For prescriptive not applicable, Performance-Based Design (PBD) methods recognize eligibility according to scenario definition, quantification of the design fire, and assessment of trial solutions (which can include compensatory measures like fire sprinklers or fire alarm systems). For suitable instances, analytical verification or testing can also serve to meet the demand without destructive tests (as with massive timber door calculations or suitable steel elements). A formal decision path breakdown identifies whether analytical or prescriptive pathways can be followed with associated factors to consider (e.g., effect on overall building performance for fire safety or requiring extra calculations or tests as indicators of age or intervals between component inspections) (McNamee et al., 2023, Figure 6). EU classification and certification considerations. The classification according to EN 13501-1 includes the reaction to fire classification system with product classes associated with a set of-reference scenarios that include ignition, growth to flashover, post-flashover, and goes up to flashover. Higher product classes reveal improved behaviour regarding the corresponding parameters. Product A1 is considered to contribute neither to the growth of fire nor to the fully developed fire. Results obtained under more demanding conditions can be considered applicable to less demanding conditions. Documentation of classification is not typing approval or certification per se (EN 13501-1: 2018 Annex A; Commission Delegated Regulation 2016/364). For the Construction Products Regulation (CPR), products sold with a harmonised product standard (hEN) must be CE marked. For second-hand products, there is no CE marking through the initial harmonised route. An EAD document should instead be developed or a national path to certification can be created. It is at least as high as the relevant hEN for similar new products. For open trading of large components in large reuse tasks, a proper certification mechanism is obviously needed (McNamee et al., 2023; Construction Products Regulation (CPR)). Implications for practice. Successful reuse within the confines of fire-safety regulations depends on the following: (i) timely detection of applicable regulations and their evolutionary changes; (ii) well-Documented information with assessment of the component's condition; (iii) well-defined choices between documentary documentation, analytical verification, testing, or PBD with corresponding compensatory actions; and (iv) availability of certification procedures that accept the reuse component with a similar level of safety equivalent to CE-marked new products (McNamee et al., 2023; EN 13501-1, 2018 ; CPR.2024).

2.3.4 Technical & logistics (design for reuse, reverse logistics, standardization)

Design for reuse and circular operation across the lifecycle:

A cyclical-built environment demands action at every stage of the material lifecycle: production, design, construction, operation, and disposal to keep materials in valuable cycles for as long as possible (European Commission, Joint Research Centre [JRC], 2024a; European Environment Agency/ETC, 2020). At the design stage, actions include designing assemblies that can be easily disassembled with low effort; designing resilient structures with a high reuse potential; designing materials that are well-suited in size to their purpose; and nature-based infrastructure. Level(s) tools facilitate the optimal design and operation and can close knowledge gaps between design intention and performance (JRC, 2024a). At the construction stage, designing a material passport, sorted selectively during demolition on site, and designing with buildings and construction products using Building Information Modelling (BIM) to retain material value through the lifecycle is encouraged (JRC, 2024a; JRC, 2024b). At the operation and maintenance stage, actions include updating material passports/BIM models, designing contracts according to performance, and designing materials and products for repair or renovation (JRC, 2024a). At the disposal stage, actions include material-passport-based pre-demolition audits or assessments; material-passport-based means of decontamination; sorting high-grade materials at their place of production; material-passport-based selective demolition; designing materials with buildings and construction products for suitable reuse/recycling (JRC, 2024b; European Environment Agency/ETC, 2020).

Two interlocking frameworks organize circular action at C&DW:

• 3R framework during the pre-construction, construction/renovation, demolition phases of projects to leverage "reduce, reuse, recycle" and "industrial symbiosis" (European Environment Agency/ETC, 2020).

• CE framework with a focus on the C&DW industry at five lifecycle levels (Pre-construction; Construction/Renovation; Collection; End-of-life; Material Recovery/Recycling) to minimize waste production and enhance the usage of recycled materials in construction (JRC, 2024b).

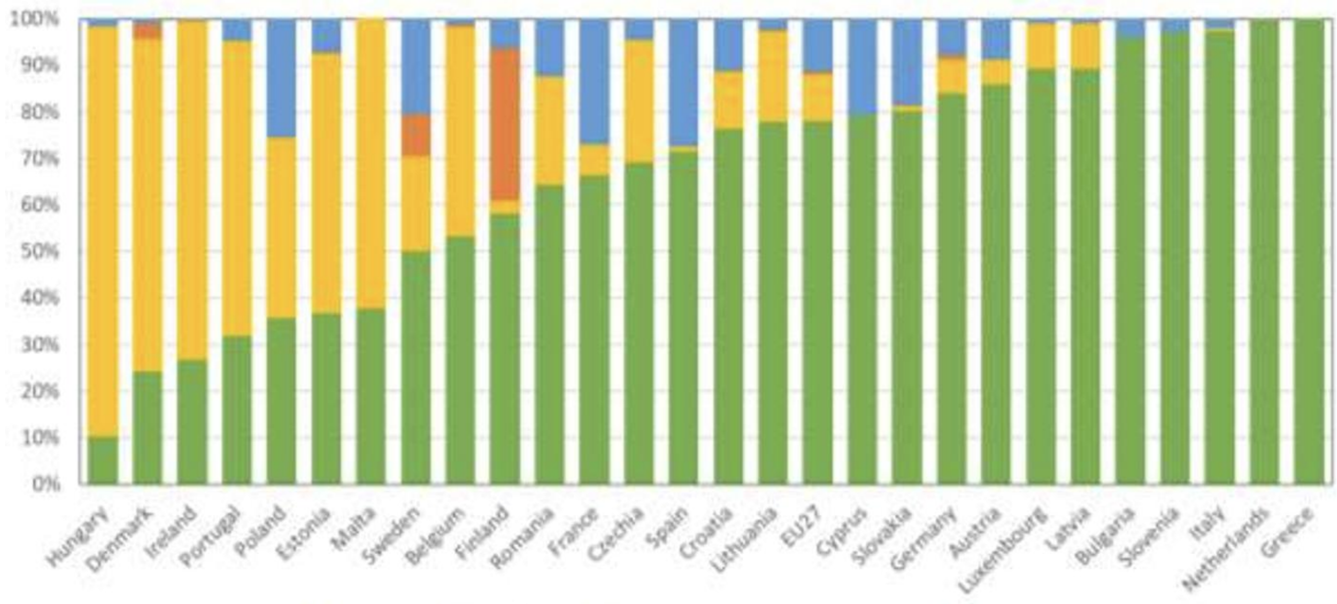


Figure 5. Treatment of the mineral fraction of CDW in the analysed EU Member States in 2020.Source: European Commission, JRC (2024)

Technical Acceptance Paths for Reused Components

For products related to fire safety standards, there are two possible technological paths (Fig. 6 of the source): Prescriptive: reuse is valid if documentation/markings ensure correct classification and visual inspection reveals no harmful signs of aging. Performance-based/analytical (PBD) — when classifications are absent or historic, with analytical or tested proof of compliance possible, or compensatory measures (such as sprinklers or alarms) are employed. It is possible to have a PBD process with principles that do not require destructive testing (PBD process principles). These pathways are required because "over time, changes to operational demands (for example, the adoption of smoke-tightness S200 to stairwell doorsets in 2011) may render prescription-based reuse of existing products impossible unless performance can be proved (overview of fire reuse in Swedish building legislation)" (McNamee et al., 2023).

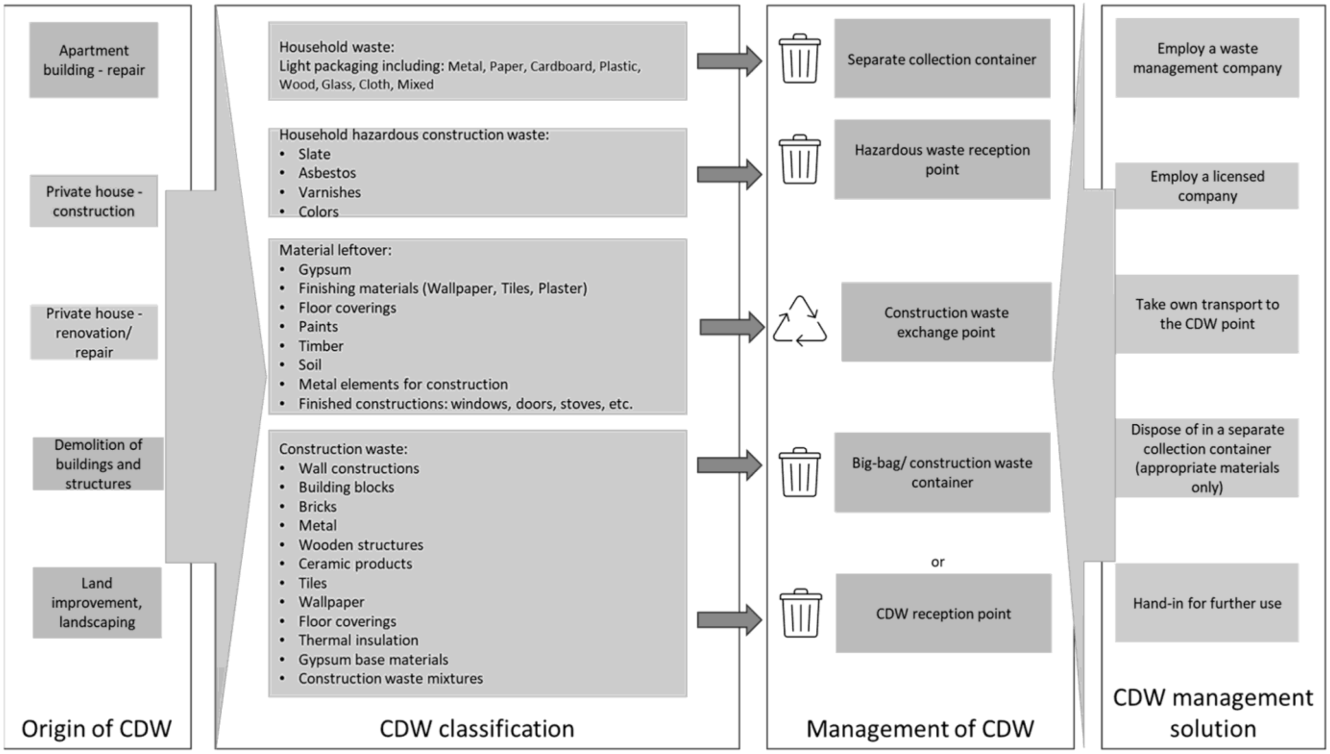


Figure 6. CDW sorting process—origin streams, classification, and management routes. Source: Overstreet (2023), ArchDaily.

Reverse logistics and sorting – Flows, facilities, and distance

Source segregation and routing begin efficient reverse logistics with separating collection bins, receipt points for hazardous waste, construction waste exchange points, big bags/containers or receipt points, then proceed to management solutions (approved contractors with transport to CDW points or deposits for collection) as indicated in the sorting process diagram (Figure 10 in your excerpt). Construction CDW recycling or recovery sites form essential nodes in the reverse logistics chain; viability is transport-distance-sensitive — in cases of longer transport, landfill charges can be offset by transport costs and contractors resort to dumping CDW (JRC, 2024b; European Environment Agency/ETC, 2020; Cudecka-Purina et al., 2024). An established market for recycled materials relies on recyclable material supply security with material quality and price structures and market demand; governments form a vital enabling factor through economic support measures (JRC, 2024b; Cudecka-Purina et al., 2024).

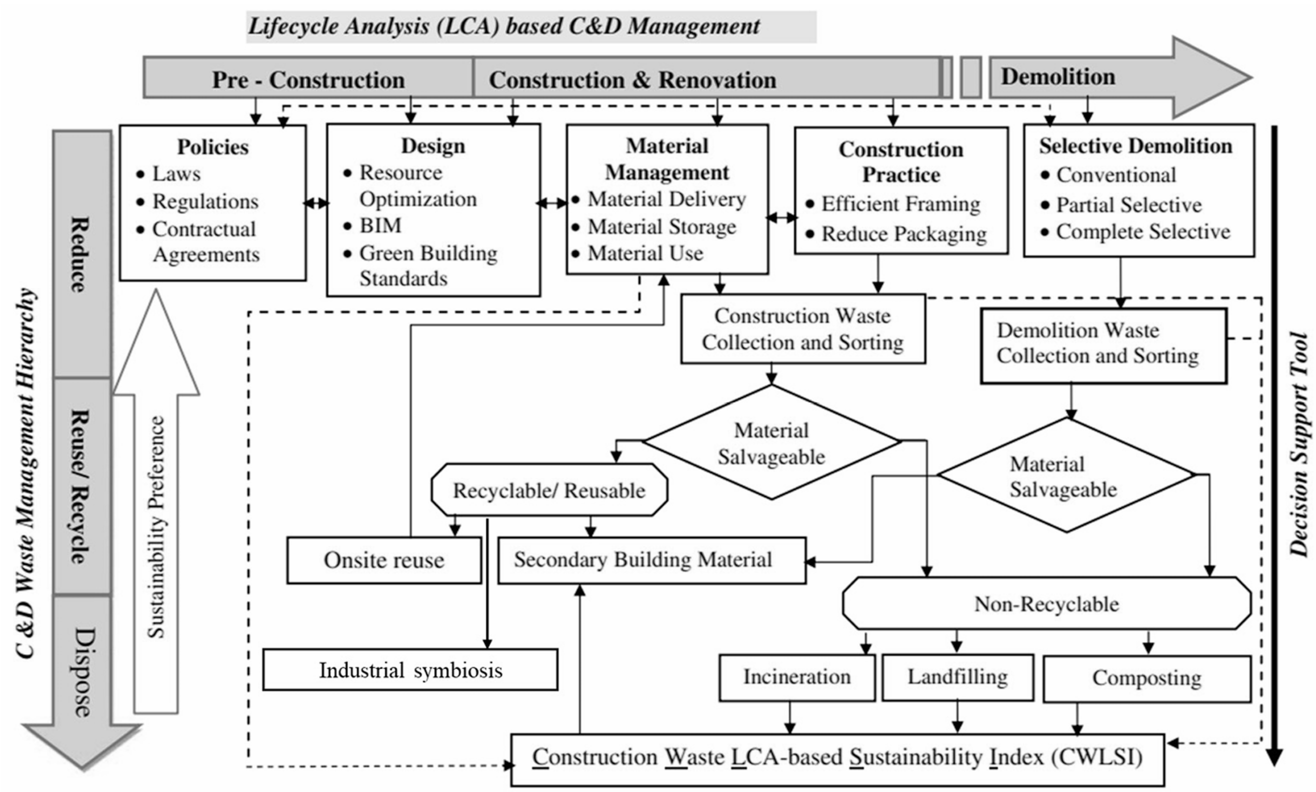


Figure 7. Theoretical framework for lifecycle-based integrated CDW management. Source: Yeheyis et al. (2013).

Standardisation, Data Quality and Reporting Challenges

Strong logistics and design for reuse require standardization and comparable data. In the EU-27, the mineral part of CDW has an average of 79% recycling rates, 10% backfilled rates, and 11% sent to landfill (Eurostat, 2020). Higher backfilling percentages have been reported for certain Member States: Hungary 88%, Denmark 71%, Ireland 73%, and Portugal 63%, with incineration with energy recovery reported for the Nordics — above 30% in Finland, around 9% in Sweden, and less than 4% in Denmark. But non-uniform data collection methods (lacking harmonisation) and varying effects or concepts of backfilling undermine comparison (European Commission, 2020c; Moschen-Schimek et al., 2023; European Environment Agency/ETC, 2020). The major key factors impacting comparison include non-standardised data collection practices and non-standard or non-uniform usage/conception of backfilling. Misallocated treatment codes of waste impede inter-country analyses (Moschen-Schimek et al., 2023; European Environment Agency/ETC, 2020).

Material-specific findings emphasize the importance of standards to logistics planning. Bricks have small but insignificant reuse rates (e.g., Denmark ~3 million bricks per year prepared for reuse ≈ 6,600 t per year; 3% of total brick waste in Denmark), while gypsum and mineral wool have low reuse rates (approx. 10% for gypsum; 2% in Switzerland for mineral wool; typically 0–1% in Flanders), with the majority going to landfill because of functional and contaminant reasons (Santoro, 2020; WRAP, 2008; Kay & Essex, 2012; Deloitte, 2017; Wiprächtiger et al., 2020; Debacker et al., 2021; Monier et al., 2011; ARUP, 2021).

Digitalisation and information systems

Material passports, BIM tools, and pre-demolition/pre-retrofitting audits regularly top the list of enabling tools to record potential reuse, facilitate selective demolition, and establish material inventories. Artificial intelligence and digitalization help to improve information availability and facilitate a cyclical business model. Pilot projects ensure rapid market transfer (JRC, 2024a; JRC, 2024b).

Implications for implementation

Technically credible reuse requires (i) early decisions on disassemblability strategies; (ii) structuring reverse logistics chains with segregation at source and treatment capacity; (iii) information retention through audits, passports, and BIM; (iv) alignment on standards and reporting to enable comparison of flows (JRC, 2024a; JRC, 2024b; European Environment Agency/ETC, 2020). At the systems level, policy tools (e.g., landfill taxes or bans) can ensure economic viability of 'proximity' recycling facilities and high-grade materials recovery to sustain the technical and logistical framework of closing cycles (JRC, 2024b; European Environment Agency/ETC, 2020; Resource Efficient Use of Mixed Wastes, 2017).

2.3.5. Crosscutting: knowledge / systemic barriers (awareness, coordination, skills)

Awareness and culture

Evidence obtained through the sources reveal that cultural and awareness barriers such as lack of customer engagement and reluctance to adopt the new culture in companies, as well as the continued adoption of a CE business mindset, are primary deterrents to the adoption of CE (Kirchherr, Reike, & Hekkert, 2018; Gasparri et al., 2023; Metinal & Gumusburun Ayalp, 2025). Even earlier reviews suggest that culture is less often mentioned in CE barriers (de Jesus & Mendonça, 2018). Although CE talk in companies is still confined to their CSR/environmental departments and not in their operational activities (Witjes & Lozano, 2016; Christensen, 1997; Friedman, 1970). In the evidence you have obtained related to your question among your chosen stakeholders, economic & market barriers to CE adoption have been deemed more influential or important, followed by technological barriers and then less important barriers related to societal/cultural factors (Gasparri et al., 2023; Metinal & Gumusburun Ayalp, 2025).

Coordination across the Value Chain

Systemic frictions include those that arise due to a lack of coordination among collaborating parties, time or knowledge limitations, and information incompleteness. Organizational barriers mentioned include lack of coordination between discipline-based domains, increased uncertainty for projects, the absence of time to identify credible reusable products, storage space limitations, regulations against product reuse, problems associated with guarantees and/or insurance, a lack of standards for certification, and inadequate information with regard to product history and product qualities (Kirchherr et al., 2018; Gasparri et al., 2023; Metinal & Gumusburun Ayalp, 2025) [compiled by the author from these sources].

Skills and capability gaps

Procurement advice stresses that the suppliers' understanding of CE is less informed than what the buyer thinks; thus, briefings for every shortlisted/converting supplier can be advantageous to remove confusion over aims and their implementation (European Commission, Joint Research Centre, 2024, §4.3). Engagement with the market and consultation processes through RFIs, individual encounters, and plenary-style forums can reveal information on solutions, supply chain information, problems, and additional CBMs (European Commission, Joint Research Centre, 2024, §4.2). Trust-building processes like dialogue phases, competitive dialogue/innovation partnerships, and adjudication criteria can move on to more collaborative-type behavior (European Commission, Joint Research Centre, 2024, §4.4).

Information infrastructure and data quality

Planning is made difficult due to non-harmonized data gathering and non-uniform backfilling information (European Commission, 2020c; Moschen-Schimek et al., 2023). Material-type evidence highlights the demand for harmonization and traceability: brick reuse rates lower (≈ 3 million bricks per year prepared for reuse in Denmark ≈ 6,600 t per year; ~3% of brick waste); gypsum at 10%; mineral wool at 2% in Switzerland (as usually 0–1% in Flanders); with the majority still going to landfill (Santoro, 2020; WRAP, 2008; Kay & Essex, 2012; Deloitte, 2017; Wiprächtiger et al., 2020; Debacker et al., 2021; Monier et al., 2011; ARUP, 2021). On a stock basis, aggregate EU datasets are useful for tracking purposes, with no need for bottom-up data on individual buildings at this stage (CE strategy purposes); we would appreciate your EU-27 materials stock assessment data (Zandonella Callegher et al., 2023).

Digital tools and knowledge retention

Material passports, pre-demolition/pre-retrofit auditing, and the role of BIM can be identified as continuous enablers to ensure reuse potential is recorded, support selective demolition activities, or compile material inventories both within and outside of current digitalisation or AI initiatives (European Commission, 2016; European Commission, 2019b).

To tackle cross-cutting barriers, the following is needed: (i) awareness raising among consumers and internal decision-makers, (ii) organized coordination through CE briefingings and dialogue-based procurement, (iii) capacity building in the chain, (iv) sound information systems (audits, passports, and BIM), and (v) harmonized reporting formats to facilitate comparison and planning (European Commission, 2020c; Moschen-Schimek et al., 2023; Gasparri et al., 2023; Metinal & Gumusburun Ayalp, 2025).

2.4 Overview of Building Assessment Protocols

Role and Development of SBRSs

Sustainable Building Rating Systems (SBRSs) or "green building rating systems/building certifications" act as a factor in "design, construction, and operation aimed at minimizing environmental impacts" (Ade & Rehm, 2020) and a means of tracking decarbonization in the building stock (UNEP, 2022). Emerging and developing for more than three decades with localized as well as global projects (Ming Shan & Hwang, 2018), SBRSs developed from a purely "green" theme to incorporate social, economic, and governance criteria, making it increasingly complex (Varma & Palaniappan, 2019) in "capturing multifaceted issues in building performance" (Doan et al., 2017). Beginning with BREEAM in 1990 in the UK, it was purely commercial at that point but soon extended to "accommodate a range of building types while encouraging local initiatives globally" (Ade & Rehm, 2020; M. Shan & Hwang, 2018), including localized versions (Mattoni et al., 2018) in multiple countries (Lazar & Chithra, 2021) after its predecessor. Second-level indicators coded against circular economy strategy/stage with our protocol-independent system, based upon a recent comparative analysis template (Lucas & Löschke, 2025) (see Figure 8).

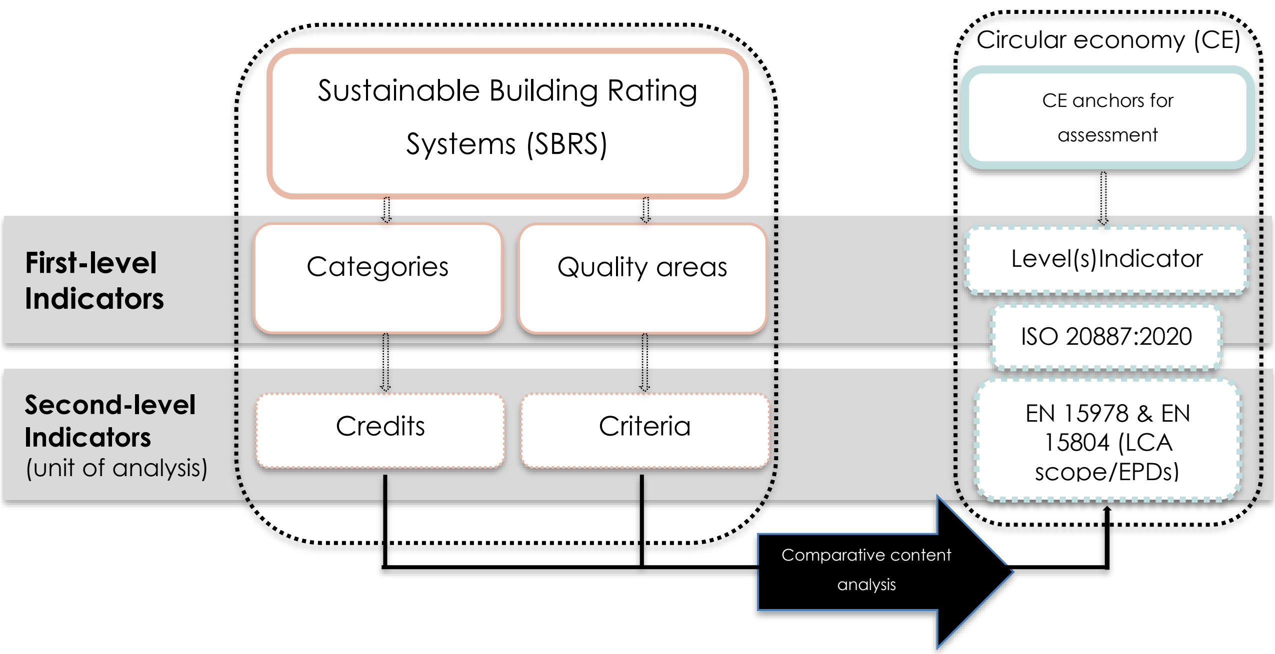


Figure 8. Standards-anchored comparative template. SBRS credits/criteria (left) are mapped to CE anchors (right): Level(s) 2.4 design-for-deconstruction checklist and minimum part-scope; ISO 20887 design aspects for DfD/adaptability; EN 15978/EN 15804 to frame life-cycle trade-offs.

How comparisons are done in systems

Within schemes, differences emerge in terms of whether systems are mandatory or voluntary in implementation, holistic or thematic in coverage, of low or high ambition, qualitative or quantitative in assessment, and locally based or globally based in terms of geographical area (Ade & Rehm, 2020). Studies include bibliographic analysis (Lazar & Chithra, 2021; Zhao et al., 2019), system comparisons (Doan et al., 2017;

Mattoni et al., 2018; Mattinzioli et al., 2021), system evolution or trends (M. Shan & Hwang, 2018; Wang et al., 2024; Wu et al., 2021), or integration studies with other systems (Braulio-Gonzalo et al., 2022; Chen et al., 2015; Ferrari et al., 2022; Goubran et al., 2023; Sánchez Cordero et al., 2019; Vitale et al., 2021).

What is found in intercomparison results

By comparison, barriers to adoption continue in housing because of costs of certification (Ade & Rehm, 2020; Darko & Chan, 2017) that will have to be considered. There is greater weightage to new constructions in many initiatives and applied approaches to renovation and EoL circularity are less clear (Ade & Rehm, 2020; Jiménez-Pulido et al., 2022; Braulio-Gonzalo et al., 2022) although renovation/renatal activities are of increasing concern in many developed countries today. In a pairwise comparison of major standards, it is seen that while mainly environmental performance metrics get priority in assessment in LEED and BREEAM standards—environmental performance considered through an emphasis on energy—DGNB focuses its prioritized attention more or less equally upon social, economic, as well as environmental performance metrics while also addressing "life cycle thinking in a clear and explicit manner" as is its aim (Doan et al., 2017; Mattoni et al., 2018; Varma & Palaniappan, 2019). There are differences in category structure and evidence as well whereby Technical Quality domains or segments are considered in DGNB in a manner that is separate and unrelated in terms of Sociocultural & Functional Quality domains too, while it is based upon "

Problems of point scoring systems and why there is a need for life cycle metrics

Issues of embodied carbon impacts, adaptation at a regional scale, after-certification building performance, and innovation rewards have been exposed through comparative assessments of different systems (Berardi, 2013; Cole, 2005; Doan et al., 2017; Newsham et al., 2009; Scofield, 2013; Sharifi & Murayama, 2013). Whole-Building Life-Cycle Assessments (WBLCA) mitigate such problems through a holistic assessment of impacts in line with standard criteria (EN 15978/EN 15804) (Anand & Amor, 2017; Pomponi & Moncaster, 2016). WBLCA is data-intensive and can be supported by BIM technology as well as new digital technology (Cabeza et al., 2014; Cavalliere et al., 2019; Robati et al., 2016; Santos et al., 2019; Shadram et al., 2016; Soust-Verdaguer et al., 2017; UK BIM Framework, 2024; BSI Standards, 2013).

2.5 SBTool/ITACA: Flexibility and CE Limitation

2.5.1. What SBTool is (generic framework, flexibility, modules)

SBTool is a generic building performance assessment tool, which can be tailored by approved organizations such as municipalities and NGOs to provide regional rating systems for categories of buildings. It can also be used as a tool for owners/managers of large portfolios to set performance criteria, as well as an education tool, as it can be quite instructive to develop a set of criteria on a variety of issues (iiSBE, 2012a).

Scope & adaptability

SBTool has a scope from pre-design, through design, construction, and operations; covers both new construction and renovation; accommodates up to three occupancy categories per building; provides both relative and absolute results; and keeps the Site and Building modules distinct. The criteria are meant to be localizable. The Design phase criteria can range from a Maximum set—approximately 115 criteria potentially in play—to a Minimum set of 12 criteria. The quasi-objective weighting procedure is set out in iiSBE (2012a, 2012b).

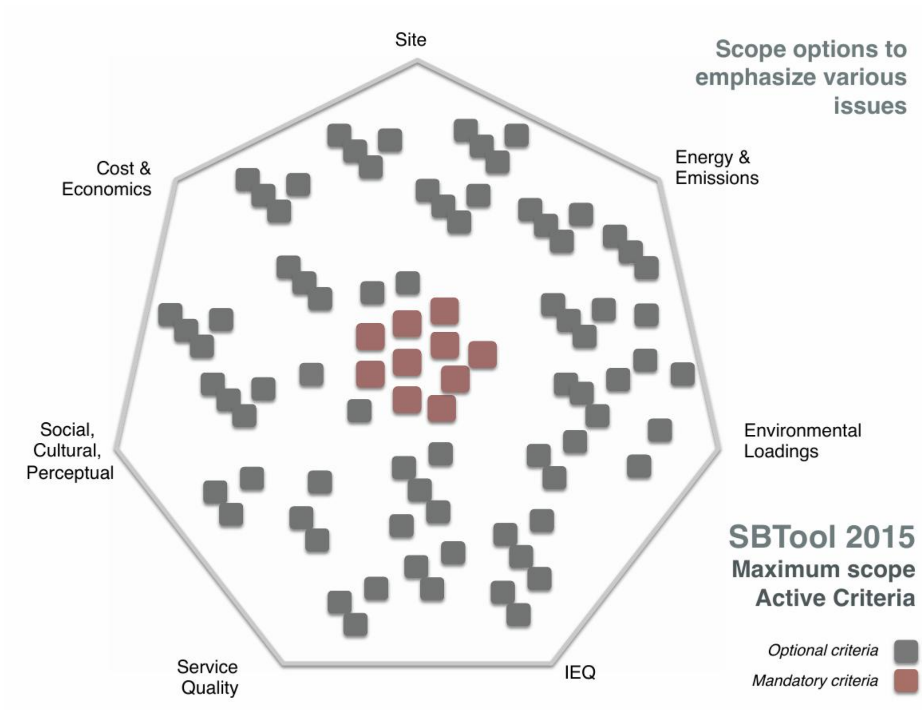
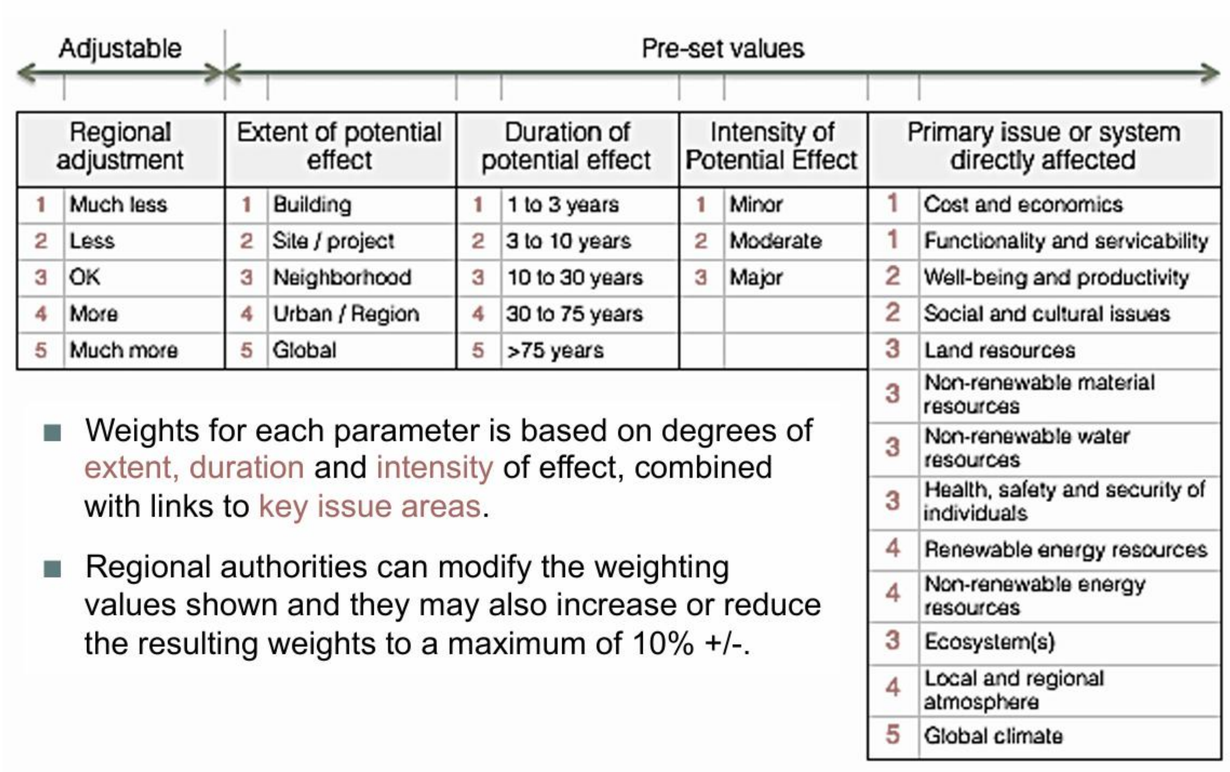


Figure 9. SBTool at maximum scope. Source: iiSBE (2015).

Figure 9. Shows the distribution of active criteria across issue areas, distinguishing optional (grey) from mandatory (red) items—illustrating configurability rather than a fixed checklist.

Set-up

The approach has been set up using two interrelated Excel spreadsheets: File A (a public/NGO set-up to establish local weighting standards for generics, consisting of a Site assessment module and a Buildings assessment module), while File B project spreadsheets for design teams include an IDP support module and self-assessment, with set-ups from multiple projects being transferred in File B (iiSBE, 2012b).



Adjustable | Pre-set values

Regional adjustment		Extent of potential effect		Duration of potential effect		Intensity of Potential Effect		Primary issue or system directly affected	
1	Much less	1	Building	1	1 to 3 years	1	Minor	1	Cost and economics
2	Less	2	Site / project	2	3 to 10 years	2	Moderate	1	Functionality and servicability
3	OK	3	Neighborhood	3	10 to 30 years	3	Major	2	Well-being and productivity
4	More	4	Urban / Region	4	30 to 75 years			2	Social and cultural issues
5	Much more	5	Global	5	>75 years			3	Land resources
								3	Non-renewable material resources
								3	Non-renewable water resources
								3	Health, safety and security of individuals
								4	Renewable energy resources
								4	Non-renewable energy resources
								3	Ecosystem(s)
								4	Local and regional atmosphere
								5	Global climate

- Weights for each parameter is based on degrees of extent, duration and intensity of effect, combined with links to key issue areas.
- Regional authorities can modify the weighting values shown and they may also increase or reduce the resulting weights to a maximum of 10% +/-.

Figure 10. SBTool weighting algorithm. Source: iiSBE (2012a).

Known limitations

The activation of numerous criteria leads to a long development time for a benchmark; many activated criteria have very small weights. Commercial adoption is limited; a small or mid-size scope focusing on thematic priorities is recommended (iiSBE, 2012a).

National adaptations (examples)

- **SBToolPT:** The residential module, SBToolPT-H, has been implemented in Portugal since 2007; aims include adaptation to the Portuguese context, harmonization with CEN/TC 350, encompassing the three sustainability dimensions, as well as a reduced but adequate set of parameters (iiSBE, 2012a).

- **SBToolCZ (2010, residential/design phase):** 33 criteria, structured as Environmental, Social, Economics & Management criteria, with a set of Locality criteria, following Czech/EU standardization, based on SB Alliance's main indicators (iiSBE, 2012a).

2.5.2 ITACA (Italy): structure, scoring scale, management & standardization

The ITACA Protocol evaluates the energy and environmental sustainability of buildings. It has been set up by the Conference of Regions through ITACA, a national association of Regions/Autonomous Provinces, in collaboration with ITC-CNR, as a means to achieve objective/measurable targets for public incentives, which has been later implemented by Regions and Municipalities by laws, regulations, public notices, and plans (UNI, 2025).

Use cases

(i) Supporting design and preventive performance analysis (public/private); (ii) control/guidance for Public Administration; (iii) supporting consumers in understanding expected performance; (iv) valorization for investors (UNI, 2025).

Method elements

Objectivity/standardization is ensured through indicators and verification procedures conforming to standards. Each criterion establishes a need (objective), a performance indicator—quantitative or scenario-type qualitative—a reference point for scoring, as well as a weight. The synthesized result indicates improvement on a −1 to +5 scale, based on a standard, according to UNI criteria (UNI, 2025).

Typologies & areas

There are many protocols available depending on use (residential, office, mall, and industrial), as well as for new and existing buildings. Commonly considered areas include Site quality, Resource consumption, Environmental loads, Indoor environmental quality, and Service quality (UNI, 2025).

Standardization (UNI/PdR 13)

Since 2015, ITACA has been rendered UNI/PdR 13—Part 13.0 (general framework and methodological principles), 13.1 (residential), 13.2 (non-residential)—so as to be consistently applied on a national basis, according to the requirements of CAM in public procurement (UNI, 2025; UNI, 2023a; UNI, 2023b). The 2025 revision of 13.0 introduces Appendices B–D on the role of the inspector/expert, as well as third-party conformity assessment, for Type A, B, and C Inspection Bodies (UNI, 2025). The criteria lists applicable to our case include those of B.3 Materials (such as B.3.4 Recycled materials, B.3.8 Certified materials, B.3.3 Renewable materials, B.3.5 Local materials, B.3.6 Disassembly of the building), as well as, in non-residential buildings, B.3.7 Adaptability for future uses (UNI, 2023a; UNI, 2023b).

2.5.3 CE anchors for assessment (neutral yardsticks)

This dissertation employs the EU Level(s) scheme, namely the macro-objective Indicator 2.4: Design for deconstruction—as a non-committal reference basis for evaluating how SBTool/ITACA support the design steps for a cyclical approach (European Commission JRC, 2020). The assessment addresses minimum coverage of building parts (Structure, Shell, Core), as well as the following three design outcomes for easy recovery, reuse, and recycling, respectively: ease of recovery: "independent layers, mechanical/reversible, accessible" connectivity; ease of reuse: "common dimensions, modular services, future-use operational modifications"; ease of recycling: "similar/compatible materials, separability, accessible recycling pathways." Where applicable, trade-offs inform comparisons concerning life-cycle performance according to EN 15978/EN 15804 (CEN, 2011; CEN, 2013). The EU Level(s) framework establishes a set of six macro-objectives, 16 associated indicators, along with a simplified LCA approach, intended to encourage life cycle thinking as well as a shared "language" from building action to EU policies (European Commission JRC, 2020).

Minimum scope for Level(s) 2.4

The design assessment includes the bill of quantities/materials and, at a minimum, the following components, differentiated according to level of assessment: Structure (bearing structure/walls, columns, floor/roof structures, foundations), Shell (non-bearing exterior walls, façades with windows/doors, claddings/linings, roof coverings), Core (floors/ceilings/linings, non-bearing interior walls, services for lighting/energy/ventilation/sanitation). The implementation process takes a step-by-step approach from Level 1–3 (concept → design decision → as-built), along a unified, transitional assessment approach for scoring/evaluation (European Commission JRC, 2020).

2.5.4. Additional anchors used (ISO 20887; EN 15978/EN 15804)

The standard ISO 20887:2020 (Design for disassembly and adaptability) applies for qualitative verification purposes to check "what good looks like" concerning separable layers, mechanical and reversible coupling, accessible and sequenced disassembly, replaceable and modular services, and supporting documentation and marking (ISO, 2020). Building LCAs, as well as EPD regulations, are set within the life-cycle perspective as they relate to trade-offs on embodied-carbon values and product data, as explained in EN 15978 and EN 15804 (CEN, 2011; CEN, 2013).

Note on the crosswalk approach

The following cross-walk addresses the minimum scope of the Level(s) 2.4 Structure/Shell/Core, along with the associated L1.4 checklist, tailored to criteria of SBTool Generic and ITACA/UNI-PdR, while design-for-disassembly principles are subject to qualitative cross-validation against the criteria of ISO 20887, encompassed within life-cycle trade-offs as indicated in EN 15978/EN 15804 (European Commission JRC, 2020; ISO, 2020; CEN, 2011; CEN, 2013).

2.5.5. SBTool/ITACA coverage against the anchors (Level(s) 2.4 + ISO 20887)

Reference checklist (based on Level(s) 2.4)

The minimum part-scope (Structure, Shell, and Core), along with the proposed three categories of outputs—recovery, reuse, and recycling—having distinct design elements, phased implementation from L1 to L3, and common reporting formats (European Commission JRC, 2020).

Shell

- Non-load-bearing external walls
- Façades (including windows and doors)
- Cladding and internal linings of external walls
- Roof coverings and linings

Structure

- Load-bearing structural frames
- Load-bearing external walls
- External and internal columns
- Floor and roof structures
- Foundation

Core (Fit-out & Services)

- Fit out (flooring, ceilings, linings)
- Non-load-bearing internal walls
- Services: lighting, energy, ventilation, sanitation

Figure 11. Level(s) Indicator 2.4 – Design for deconstruction: minimum scope of building parts to be assessed (L2.2 "Checklist item 1"). Source: European Commission JRC, Level(s) user manual (Indicator 2.4).

SBTool (Generic)

SBTool has a configurable toolkit, including File A (public/NGO configuration) and File B (project), implemented from pre-design phases to operations, though the scope can be adjusted from 115 criteria to 12 criteria. A set of criteria within cost-recovery/DfD flexibility depends on local implementation, while a minimum part scope, as well as Levels L1 to L3 breakdown, is not stipulated in the generic iiSBE kit (iiSBE, 2012a, 2012b).

ITACA / UNI-PdR 13 (national adaptation)

ITACA employs a −1…+5 scale based on weighted criteria verifiable according to a set standard. The criteria associated with CE include B.3.6 Disassembly of the building (specified level of DfD), B.3.4 Recycled materials, B.3.8 Certified materials, B.3.3 Renewable materials, B.3.5 Local materials, and, in non-residential buildings, B.3.7 Adaptability for future uses. Supporting criteria are found in C.3 Solid waste/Land reuse and E.2 Monitoring/Documentation (UNI, 2023a; UNI, 2023b).

Cross-walk

1) Recovery simplicity: ITACA B.3.6 intends to achieve similar outcomes to the recovery concepts under Level(s) 2.4, but ITACA does not have staged checklists in an L1–L3 format, nor a mandatory minimum part-scope approach as in Level(s) (European Commission JRC, 2020; UNI, 2023a; UNI, 2023b). In SBTool Generic, a File A can trigger recovery criteria, though nothing is mandatory at the generic level (iiSBE, 2012a). **2) Reusability:** The residential level has weaker coverage compared to B.3.7 (non-residential), which explicitly addresses adaptability for future uses. The use of standard dimensions and modular services is not expressed as a checklist at the design level, as it is for Level(s) L1.4. SBTool Generic does not prescribe this unless implemented at a local level (iiSBE, 2012a; European Commission JRC, 2020).

3) Ease of recycling: ITACA considers recycled/renewable/certified materials, as well as waste (B.3.3–B.3.8; C.3), but does not provide a separability/compatibility-routes checklist as in the Level(s) L1.4 design-concepts list. SBTool Generic likewise depends on local implementation (UNI, 2023a; UNI, 2023b; European Commission JRC, 2020; iiSBE, 2012a).

Reporting & stages

Level(s) requires application and reporting at Levels 1–3, while ITACA uses criterion sheets and SBTool Generic provides relative/absolute outputs without dedicated L1/L2/L3 deconstruction report templates (European Commission JRC, 2020; iiSBE, 2012a; UNI, 2025).

LCA trade-offs

While Level(s) explicitly recommends checking Lifecycle GWP or conducting an LCA where trade-offs exist, ITACA and SBTool do not require that specific step; EN 15978/EN 15804 provide the basis when such checks are performed (European Commission JRC, 2020; CEN, 2011; CEN, 2013; iiSBE, 2012a).

Table 2. Coverage of Level(s) 2.4 "Design for deconstruction" outcomes in SBTool Generic and ITACA (UNI/PdR 13.1 / 13.2)

Level(s) 2.4 outcome (L1.4)	**SBTool Generic**	**ITACA – UNI/PdR 13.1 (Residential)**	**ITACA – UNI/PdR 13.2 (Non-residential)**
Ease of recovery (independent layers; mechanical/reversible; accessible; low disassembly steps)	Not explicit in generic kit; can be added via local File-A criteria (iiSBE, 2012a, 2012b).	Direct: B.3.6 Disassembly of the building (UNI, 2023a).	Direct: B.3.6 Disassembly of the building (UNI, 2023b).
Ease of reuse (standardised dimensions; modular services; capacity for future functional change)	Partial / implementation-dependent; no generic prescription (iiSBE, 2012a, 2012b).	Partial: residential coverage weaker; no explicit "Adaptability for future uses" criterion (UNI, 2023a).	Direct: B.3.7 Adaptability for future uses (UNI, 2023b).
Ease of recycling (homogeneous/compatible	Partial / implementation-	Partial: B.3.3, B.3.4, B.3.5, B.3.8 (materials) and C.3	Partial: B.3.3, B.3.4, B.3.5, B.3.8 (materials) and C.3

Level(s) 2.4 outcome (L1.4)	SBTool Generic	ITACA – UNI/PdR 13.1 (Residential)	ITACA – UNI/PdR 13.2 (Non-residential)
materials; separability; established routes)	dependent; may be covered through local materials/waste criteria; no Level(s)-style separability checklist (iiSBE, 2012a).	(solid waste/land reuse); lacks explicit separability/compatibility-routes checklist (UNI, 2023a).	(solid waste/land reuse); lacks explicit separability/compatibility-routes checklist (UNI, 2023b).

Legend:

Direct = explicit criterion

Partial = related criterion(s) but lacks Level(s) L1.4 design-aspect checklist or limited scope

Not explicit = no explicit coverage in the generic kit (implementation-dependent)

2.5.6. Proposed alignment (summary actions)

Adopt minimum scope

In SBTool local systems and ITACA, require the Level(s) 2.4 minimum part scope (Structure/Shell/Core) while marking results for both DfD/CE (European Commission JRC, 2020).

Include a design-stage checklist

The Level(s) L1.4 checklist should be annexed to ITACA B.3.6 (Disassembly) and B.3.7 (Adaptability, as applicable), as well as SBTool local criteria, using the wording from ISO 20887 for mechanical/reversible and accessible connections, and independent layers (European Commission JRC, 2020; ISO, 2020).

Systematize reporting

Include a brief two-part record at design stage and hand-over consistent with Level(s) L2.7/L3.6 ("parts addressed; aspects examined; design solutions; overall scores") (European Commission JRC, 2020).

Flag LCA checks for trade-offs: Where the application of DfD characteristics could affect other impacts, include an LCA note citing EN 15978/EN 15804 (European Commission JRC, 2020; CEN, 2011; CEN, 2013).

Handover of passport (Optional): For Level 3 equivalence, append the as-built deconstruction report as a seed for a building passport (European Commission JRC, 2020).

2.5.7. CE limitations in SBTool/ITACA vs anchors

No mandatory minimum part-scope (Structure/Shell/Core) in SBTool Generic or ITACA—present in Level(s) 2.4 (European Commission JRC, 2020; iiSBE, 2012a).No standardized L1–L3 staged checklist/reporting for deconstruction—required in Level(s) (European Commission JRC, 2020). The level of detail in elements associated with adaptability and disassembly is lower in ITACA (B.3.6 Disassembly, B.3.7 Adaptability—non-residential) and relatively weak in residential coverage, as detailed design features (e.g., reversible/accessible connections, standardized dimensions, modular services) are not specified like in Level(s) L1.4 (UNI, 2023a; UNI, 2023b; European Commission JRC, 2020).

Ease of recycling. Materials/EPD/waste are addressed (B.3.3–B.3.8; C.3), though not via a separability/compatibility-routes checklist (UNI, 2023a; UNI, 2023b).

Trade-off governance. SBTool Generic and ITACA do not require the Level(s) step to check LCA (EN 15978/EN 15804) when DfD choices affect other impacts (European Commission JRC, 2020; CEN, 2011; CEN, 2013).

Implementation dependency (SBTool). High flexibility, though outcomes depend on local File-A configuration; CE coverage can vary widely (iiSBE, 2012a, 2012b).

The SBTool/ITACA system has entry points for circular design—ITACA B.3.6/B.3.7 and materials/waste criteria. Harmonizing it with Level(s) 2.4 and ISO 20887 would make it clearer, staged, and verifiable, fulfilling the objective of the thesis about making the concept of circular renovation operational within building/campus-level agreements (European Commission JRC, 2020; ISO, 2020).

Chapter 3. Methodology

3.1 Seven-Step Research Flow

The approach taken for the writing of this thesis involves an experimental 'indicator development' process. The proposal begins with the generation of evidence, testing, refining, and validation. The proposal is broken down into seven steps. The steps include a literature review, extracting indicators, the application of CircularB COST, cross-mapping, analyzing gaps, choosing a priority gap, piloting, as well as validation. It is worth noting that the approach has been structured to start from knowledge, culminating in applying knowledge within a Politecnico di Torino campus setting.

Step 1: Targeted literature review and corpus screening– the search strategy and screening of the COST CircularB database are described in Section 3.3, while the resulting classification of the corpus is reported in Section 4.1.

Step 2: Indicator extraction and metadata coding– the hand-coding of indicators and the 15-field Excel template are presented in Section 3.5; an overview of the final indicator dataset is included in Section 4.1.

Step 3: CircularB COST classification– the use of the CircularB framework is introduced in Section 3.4 and the coding rules are detailed in Section 3.6; the corresponding classification results are summarized in Section 4.1.

Step 4: SBTool cross-mapping– the mapping protocol is explained in Section 3.7, and the empirical crosswalk between the indicators and SBTool/ITACA criteria is presented in Section 4.2.

Step 5: Key-gap selection and operationalization– the methodology for identifying and prioritizing SBTool gaps is set out in Section 3.9, the outcomes of this process are reported in Section 4.3, and the detailed formulation of the selected gap indicator within SBTool/ITACA is developed in Chapter 5.

Step 6: Case-study application– the Politecnico di Torino campus and the Digital Revolution House are introduced in Section 3.8, while the implementation of the new indicator and the case-study results are discussed in Sections 6.1–6.3.

Step 7: Indicator validation– the general validation procedure is outlined in Section 3.10; the robustness checks and validation results from the DRH application are presented in Section 6.4 and further synthesized in Chapter 7.

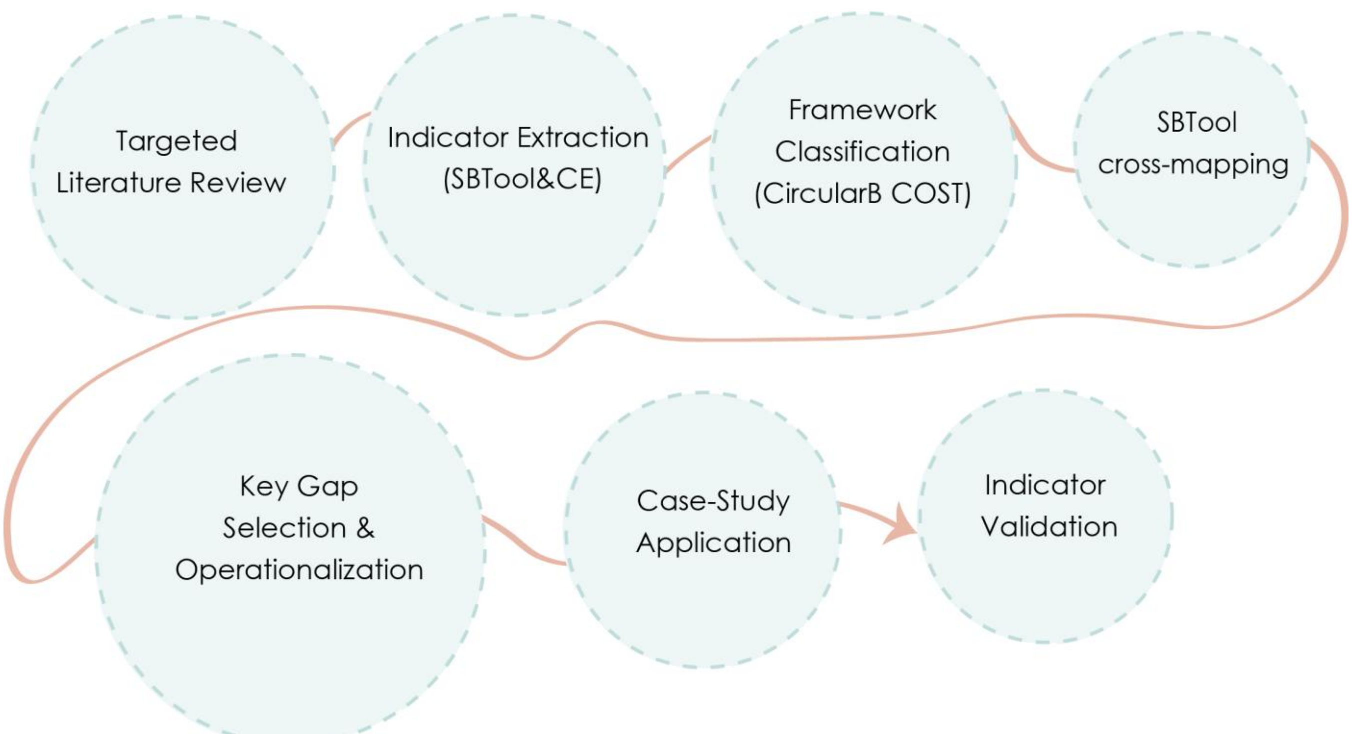


Figure 12. Research design flow from literature review to case-study validation

3.2 Purpose and Background

Purpose: The aim of this experimental thesis is to establish a specific ITACA Protocol adapted to campuses so that assessment criteria are aligned with the specific characteristics of campuses in terms of structures, functionality, and use and can become a reference model for sustainability innovation for the entire university sector.

Origins: The project was born out of a supervisor's task to (i) undertake a focused literature search concerning the circular economy and sustainability issue within the building environment; (ii) to extract indicators into a pre-defined Excel template format; and (iii) to complete the thesis according to an outline involving introductory statements concerning issues/objectives/methodology statements and structuring around both the Circular Economy in building assessment/SBTool, description of CircularB's approach or methodology to data interpretation to focus on results concerning 'Mapping & Classifications' interpretation with proposals to adapt SBTool to conclude with 'future work' referencing.

3.3 Corpus & Screening (15 papers)

Rather than initiating a conventional keyword sweep across multiple databases, this review capitalised on a curated corpus of 29 articles supplied through the COST Action CA17133 CircularB Taskforce. The parent CircularB repository comprises 266 peer-reviewed studies, each pre-vetted for relevance to sustainability and Circular-Economy. Leveraging this expert-filtered set aligns with the experimental scope of the thesis—indicator extraction and protocol refinement—rather than an exhaustive bibliometric census.

	A	B	C	D	E
1		Nr. (ID)	Indicator	If no, why?	
2	225	546	No	expert perceptions an	Experts' Perceptions of the Management and Minimisation of Waste in the Australian Construction Industry
3	226	548	Yes		Climate and resource footprint assessment and visualization of recycled concrete for circular economy
4	227	549	No	Paper inaccessible du	A Life Cycle Analysis Based Framework to Promote Circular Economy in the Building Sector
5	228	550	Yes		Waste management planning toward zero waste in Hotel XYZ Bandung with circular economy principles (case study: Room service fac
6	229	552	Yes		Decision Framework to Balance Environmental, Technical, Logistical, and Economic Criteria When Designing Structures With Reused C
7	230	558	Yes		Complete Circularity in Cross-Laminated Timber Production
8	231	559	No	It's a methodological r	Methodological review: Socio-cultural analysis criteria for BIM modeling and material passport tracking of agriwaste as a building cons
9	232	562	Yes		Circularity Assessment using the un 2030 Agenda Indicators
10	233	563	No	Paper inaccessible du	The paradigm of circular economy in heritage preservation of southern Chile; [O Paradigma Da Economia Circular Na Conservação Pa
11	234	564	Yes		Circular Construction Process: Method for Developing a Selective, Low CO2eq Disassembly and Demolition Plan
12	235	565	No	Methodological LCA p	Towards circular life cycle assessment for the built environment: A comparison of allocation approaches
13	236	567	No	Paper inaccessible du	CIRCULAR ECONOMY (CE) BASED MATERIAL SELECTION: DEVELOPMENT OF A CE-BASED '10R' EVALUATION FRAMEWOR
14	237	568	No	Methodology/financial	Building energy retrofit-as-a-service: a Total Value of Ownership assessment methodology to support whole life-cycle building circulari
15	238	570	No	Conceptual/policy pap	Redesigning public governance of the Danish built environment from relative to absolute metrics
16	106	187	Yes		Potentiality of earth-based mortar containing bamboo particles for GHG emissions reduction
17	107	188	Yes		Matching algorithms to assist in designing with reclaimed building elements
18	108	189	Yes		Life cycle assessment and economic analysis of Reusable formwork materials considering the circular economy
19	109	190	Yes		Comparison of environmental assessment methods when reusing building components: A case study
20	110	192	No	(B1–B25); methods =	Barriers to circular economy practices during construction and demolition waste management in an emerging economy
21	111	199	No	paper develops a	Reducing CO2 Emissions and Improving Water Resource Circularity by Optimizing Energy Efficiency in Buildings
22	112	200	No	mentions indicator	Causal Effects between Criteria That Establish the End of Service Life of Buildings and Components
23	113	201	Yes		Improvement of Environmental Sustainability and Circular Economy through Construction Waste Management for Material Reuse
24	114	206	Yes		Indicators to Measure the Management Performance of End-of-Life Gypsum: From Deconstruction to Production of Recycled Gypsum
25	115	208	No	Urban-level indicator	Build up circular city planning index with EAM
26	116	210	Yes		Material stocks in Germany's non-domestic buildings: a new quantification method
27	117	217	Yes		Digitizing material passport for sustainable construction projects using BIM
28	118	218	No	a research-maturity	Recycling Waste Construction Material and Industry Involvement in University Investigations: Developing a Framework
29	119	221	Yes		Implementation of the New European Bauhaus Principles as a Context for Teaching Sustainable Architecture
30	120	222	Yes		Comprehensive Sustainability Assessment of Regenerative Actions on the Thermal Envelope of Obsolete Buildings under Climate Chan

Figure 13. Screened Sources

For transparency, the list underwent a screening criteria:

1. Scale relevance – the study had to address buildings or building components; neighbourhood- or city-scale papers were excluded.
2. Indicator presence – the text had to report at least one measurable CE/sustainability indicator (quantitative, semi-quantitative, or rigorously defined qualitative).
3. Language and access – the full text had to be available in English through the Politecnico di Torino library system.

Outcomes of screening:

1 paper excluded for language (Spanish, no English full text).

2 papers excluded for inaccessibility (no full text).

Additional items excluded for content/scope reasons, e.g.:

– Methodological perspective proposing concepts (BIM + materials passports + socio-cultural factors) without KPIs, formulas, scales, or thresholds.

– Barrier’s study (e.g., RII/FA/regression) reporting perceptions/relations but no KPI definition;

– Review article naming “indicator families” without measurable definitions at building/component/system level.

– Urban-level indicator outside building/sub-building scope.

After applying these criteria, 15 papers remained and formed the final corpus used for indicator extraction and the subsequent methods (classification and cross-mapping). Reasons for exclusion were logged in the register to ensure transparency and reproducibility.

Table 3. Inclusion and exclusion criteria applied to the CircularB corpus.

Criterion	**Inclusion (+)**	**Exclusion (–)**	**Rationale**
Scale	Building, building-component, or whole-building system	Urban/neighbourhood studies, product supply-chain only	Thesis focuses on building-level upgrades to SBTool
Indicator presence	At least one measurable or clearly defined indicator, metric, score, or index	Conceptual discussion with no indicator definition	Ensures extraction yields concrete data
Language	English full text	Non-English or abstract only	Facilitates peer checking and reproducibility
Accessibility	Full text available via Polito library or open access	Pay-walled or missing files	Data integrity—indicators must be verifiable

3.4 Framework Used: CircularB COST

Aims and rationale

CircularB (COST Action CA21103) aims to create a common international framework for building-circularity assessment with a rating system based on Key Performance Indicators (KPIs), which are aligned with the European Circular Economy Action Plan. The Action Plan focuses specifically on local adoption across multiple countries and the incorporation of Open BIM to enable automated assessment for circular building design (CircularB, n.d.; COST, 2022; European Commission JRC, 2017).

Objectives

A) Research-coordination objectives

The Action coordinates policies relevant to COST members; compiles data regarding construction methods, innovative materials, and solutions; compiles data regarding methods for rehabilitating or adaptive reusing buildings/construction components; develops understanding regarding implementation methods for CE principles based upon feasible action-items/guidelines; identifies KPIs and develops an international framework (ready for an Open BIM API); connects the KPI framework to Level(s); adjusts to regional benchmarks; evaluates implementation of the CEAP in building construction; investigates business-model or market-application options; develops anthropogenic-resource localisation methods based upon adaptive-reuse strategies; and distributes results, including capacity building (CircularB, n.d.; COST, 2022).

B) Capacity-building objectives

The Action creates new skill sets related to CE for owners, design professionals, engineers, contractors, economists, and policymakers; encourages policymakers to embrace specific approaches to CE; fosters collaboration across sectors in the value chain; offers opportunities to Early-Career Investigators and Inclusiveness Target

Countries; provides an online platform for best practices in CE implementation; arranges workshops and training schools for sharing expertise; supports joint scientific-technical outputs with mid-term or final events; and fast-tracks knowledge sharing between R&I communities and industry communities (CircularB, n.d.).

Networking excellence and added value

CircularB is a four-year pan-European networking Action (launched late 2022), aims to consolidate scattered activities related to circular buildings to create global guidelines with a KPI set according to existing schemes like Level(s)(Karaca, 2024; COST, 2022; European Commission JRC, 2017).

Critical mass and stakeholder involvement

The Action involves a large community—academia, SMEs, NGOs, research institutions, industry, and public bodies—across several COST countries. Publicly available lists of members/guests in MEs/WGs or Action sites denote a multidisciplinary and cross-country character to workshops/webinars/seminars, training schools, and short-term scientific missions (COST, 2022; CircularB, n.d.).

WG3 scope: Circular KPIs framework (alignment with this thesis)

Aim. WG3 develops relevant, reliable, and replicable circular KPIs to evaluate the circularity index of both new and existing residential buildings. These KPIs are to be used in COST member states and categorized into Governmental/Institutional, Environmental, Social, Economic, and technical dimensions. These are considered complementary to well-known sustainability assessment schemes (CircularB, n.d.).

T3.1 Identify and describe existing criteria defining/evaluating circular-strategy implementation in buildings.

T3.2 Strengths/weaknesses analysis for available methods related to circularity/sustainability.

T3.3 Create a Circular KPIs Dashboard and identify KPIs to develop.

T3.4 Create datasets for partner countries (priority strategies, customs, culture). T3.5 Propose a framework for international-system KPIs to prioritize/select new or existing buildings based on weights related to benchmark assessment. T3.6 Assess sustainability added value and relate to Level(s); evaluate integration with other schemes (e.g., SBTool).

T3.7 Define the KPI integration and automation layout in BIM for circular assessment of BIM models (CircularB, n.d.).

A pre-defined Excel-based register was used to record individual indicators in one row per indicator with carefully defined and auditable columns. The template consists of four parts:

(1) "Identification & source" (No., Paper ID, Indicator name, Acronym, verbatim definition including page, authors/year/DOI/link, developer type);

(2) "Scope & context" (element level, building use, intended life-cycle stage, sustainability linkage, scope/context statements);

(3) "Measurement & status" (quantification level; unit/metric; digital tools used; testing/validation performed; reviewer);

(4) "Method provenance" (development methodological-approach check boxes for literature/tool-based development, surveys/interviews conducted, empirical case studies undertaken, simulation/LCA scenario development, coding consultation related to standards/codes/policies, additional remarks).

In its implementation within this doctorate project, the data-collection method remains purely a methodological tool to enable traceability (definition verbalized + page), to enable inter-study comparison (notably defined unit/unit level), and to enable recreation (coded details for scope elements/life-cycle use, building use, context statements/methods used), which provides input exclusively for these subsequent steps related to classification according to CircularB logic and mapping individual indicators to SBTool Issue ⇒ Category ⇒ (Criterion).

3.5 Indicator-Extraction Protocol (Excel + 15-Field Metadata)

The 15 eligible articles were processed in three sequential steps to convert the screened sources (section 3.3) into harmonized, auditable indicator records that can be used directly for classification and SBTool cross-mapping. This section specifies the workflow and the metadata captured.

Figure 14. Indicator Extraction Process

Document preparation

Each full-text PDF was renamed to match its Paper ID in the master spreadsheet (e.g., 546.pdf, 548.pdf) and stored in a dedicated project folder. This numeric convention ensures one-to-one alignment between the corpus list and the extraction sheet, eliminating the risk of duplicate or misplaced files.

Manual Coding Protocol

The manual coding protocol converts unstructured textual evidence into a harmonised indicator dataset suitable for cross-framework comparison. The unit of analysis is each building-scale performance indicator explicitly defined in a source paper. Coding proceeds at the indicator level, not at the article level, to preserve multiple distinct metrics reported within a single paper.

Metadata fields

To ensure that every indicator could be traced, interpreted and—ultimately—compared with the SBTool criteria, a compact metadata scheme was designed for the extraction spreadsheet.

Each record (column) in the file captures 15 core attributes, grouped into logical clusters that follow the flow from bibliographic identity to methodological provenance.

Table 4. Fifteen-attribute metadata template used for coding each indicator

Cluster	Attribute	Brief purpose in the dataset
Bibliographic identity	1. Paper ID 2. Authors 3. Year 4. Link to publication	Uniquely tags the source paper and provides basic citation data.
Indicator description	5. Indicator name 6. Acronym 7. Definition	Gives the canonical label, any widely used shorthand, and a concise operational definition.
Contextual positioning	8. Level of element in building composition 9. Building uses 10. Use in life cycle 11. Consideration of contextual factors	captures an indicator's spatial granularity, functional domain and temporal slot within the building life cycle, while also flagging whether its calculation depends on localized inputs. Collectively, these four tags define the complete situational envelope in which the metric is meant to operate.
Sustainability linkage	12. Sustainability linkage	Maps the indicator onto headline sustainability domains.
Quantification & provenance	13. Developer 14. Assessment type / Level of quantification 15. Development methodology	identifies who originated the metric, specifies its measurement level and summarizes the method by which it was derived.

Detailed coding rules for each attribute and the rationales for their sub-categories are presented in later subsections. This structured approach guarantees that every extracted indicator is:

1. Citable
2. Readable
3. Comparable
4. Auditable

Collectively, the fifteen metadata fields provide the minimum viable information set for robust cross-mapping to SBTool while remaining light enough for rapid hand-coding during the extraction phase.

3.6 Classification with CircularB COST

The classification step organises the extracted indicators into a consistent structure so they can be compared across sources and then cross-walked to SBTool without altering the underlying evidence.

The working dataset comprises 53 building-scale circular-economy/sustainability indicators, recorded one per row in the register created in section 3.5.

Classification Inputs

1. The Excel register is treated as the authoritative record. For each indicator it retains all verbatim fields: indicator name, page-referenced definition, unit or formal equation, and full bibliographic details.

2. A bounded codebook defines the acceptable categories and decision criteria for each axis, enabling consistent, repeatable coding.
3. Common notations are applied to prevent ambiguity (e.g., kg CO_2e/m^2, kWh/m^2·yr, and EN 15978 module identifiers). These conventions harmonise presentation without changing original source texts.

Classification workflow

1. Indicators were coded using the CircularB COST template with two guiding principles: consistency (one preferred value per axis) and traceability (no edits to verbatim fields). All coding decisions are anchored to the source and can be audited line-by-line.
2. Coding was performed only in the dedicated classification columns. The verbatim columns—Indicator name, Definition (with page pointer), and Unit/Equation—were locked and never altered.
3. For every indicator, one primary class was assigned on each axis:
   - System scale: Material; Component/Product/Element/System; Whole building.
   - Sustainability linkage: Environmental; Economic; Social.
   - Primary life-cycle stage: Inception/Predesign; Design; Procurement; Construction; Operation & Maintenance; Refurbishment/Adaptive Reuse; End-of-life; or Unspecified when the source did not state a stage.
   - Degree of quantification: Quantitative (unit/equation present); Semi-quantitative (anchored ordinal rubric); Qualitative (structured checklist/rubric without units).

4. Where reported by the source, boundary notes—functional unit, EN 15978/EN 15804 modules, and key assumptions—were recorded alongside the verbatim fields to preserve comparability.

Decision rules

1. Secondary tags were added only if explicitly stated by the source; otherwise, a single primary class was retained.
2. If a construct clearly spanned two options, the smallest applicable category was chosen for the primary assignment to avoid double counting in downstream mappings; any secondary applicability was noted.
3. When life-cycle stage was absent, the entry was coded Unspecified (no inference by analogy).
4. Coding targeted the composite KPI; principal sub-criteria were summarised in remarks.
5. Where multiple rows reflected the same calculation in the same source, a single canonical record was retained, and any aliases were noted.
6. Where interpretation was required, a one-line justification with page pointer was recorded.

Denominators and reporting

Because a subset of indicators is dual-applicable on certain coding axes, coverage tables are reported on an occurrence basis for any axis where multiple classifications legitimately apply.

By default, all other cross-tabulations and figures that analyse indicators as distinct units (e.g., SBTool Issue × Mapping Status) use n = 53 unique indicators (one primary class per axis). Each table/figure states its own denominator explicitly and denominators are not mixed across visuals or narratives.

Table 5. CircularB COST schema

Developer	System scale	Building use	Primary life-cycle stage	Sustainability linkage	contextualization	Level of quantification	Development methodology
Academia/ Research Institutions	Material Level	General/ Unidentified	Inception/ Predesign	Environmental	Local/ Regional	Quantitative	Literature Review & Content Analysis
Government	Component/ Product, Element or System Level	Residential	Design	Economic	Global	Semi-quantitative	Based on Previous Tool/ Indicator
NGO /Community	Whole Building Level	Commercial	Procurement	Social		Qualitative	Surveys & Questionnaires
Industry/ Consultancy		Healthcare Facilities	Construction				Interviews & Focus Groups
		Industrial	Operation and Maintenance				Empirical Data & Case Studies
		Heritage/ Cultural	Refurbishment/ Adaptive reuse				Simulation Models & Lifecycle Scenario Analysis
		Institutional	End-of-life				Building Codes & Regulatory Frameworks
		Mixed-Use					Digital Tools
							Testing & Validation

3.7 Mapping protocol

3.7.1 Purpose & Scope

This subsection establishes the crosswalk between the 53 literature-derived indicators and the SBTool hierarchy (Issues → Category → Criteria → Indicators). The purpose is twofold:

1) to quantify the current coverage of circular-economy constructs within SBTool,

2) to identify gaps where coverage is absent or under-specified, thereby informing the protocol modifications proposed in Chapter 5. The unit of analysis is the individual indicator; each is mapped to the most specific SBTool criterion (or, where unavailable, to the parent issue), with mapping states defined as exact, partial, or no match. This crosswalk provides the transparent evidence base for the coverage metrics and prioritized gap list. These mappings are read alongside the CircularB classifications developed in section 4.1 (system scale, sustainability linkage, life-cycle stage, quantification level) to avoid double counting and to focus improvements where indicators are scarce.

3.7.2 Mapping protocol and decision rules

This subsection specifies the crosswalk between the literature-derived indicators and the SBTool hierarchy. Each column captures a distinct methodological decision required to judge integration readiness (can SBTool already host the metric?) and circular-economy relevance (how does the metric contribute to circularity?).

Listing the Indicator with its Paper ID(s) preserves a direct audit trail from thesis claims to source material. Multiple IDs attached to the same indicator signal maturity/repeatability in the literature and avoid “black box” mapping.

3.7.3 Mapping status as triage:

The SBTool slot (Issue → Category → Criterion) column records the precise locus—actual or proposed—of each indicator. Writing the full path makes the mapping reproducible and lets the reader immediately see concentrations and sparse zones, which is essential for a fair gap analysis.

The 10R (primary) and Loop columns distinguish strategy from mechanism,

- 10R indicates which circular strategy the indicator serves (e.g., Reduce, Reuse, Repair/Refurbish, Recycle).
- Loop captures how the indicator acts on flows: Narrow (use less), Slow (use longer), Close (return to use), Regenerate (restore).

Including both clarifies why many Exact matches are LCA-type Reduce/Narrow metrics, whereas Partial and No match items more often target Reuse/Refurbish/Recycle and Slow/Close—precisely the areas where SBTool requires strengthening.

3.8 Case context: Politecnico di Torino campus and Digital Revolution House (DRH)

3.8.1 General description, functions and role on campus

The Digital Revolution House (DRH) is a new centre for research, advanced training and innovation promoted by Fondazione CRT in partnership with the Politecnico di Torino and the Italian Institute for Artificial Intelligence (AI4I). Funded through an overall investment of more than €40 million, of which €15 million is provided by Fondazione CRT, the project extends the collaborative model already tested at OGR Torino, creating a permanent hub for artificial intelligence and advanced digital technologies within the university campus (Fondazione CRT, 2025; Politecnico di Torino, 2025a). The building is conceived as an "interface" between these three actors and the wider urban innovation ecosystem, concentrating activities that were previously dispersed across different sites.

Figure 15. Architectural rendering of the Digital Revolution House (DRH) at the Politecnico di Torino, showing the main street façade with its external shading screen and glazed volume. Source: Politecnico di Torino, Masterplan – Digital Revolution House project page (2025).

Functionally, DRH is organised as a compact, vertically layered volume that supports a continuum from education to experimentation and applied research. The lower levels accommodate the Casa dei Team, a large laboratory and workshop area distributed between the ground floor and basement around a sunken courtyard, dedicated to student teams engaged in prototype-based projects. Above, level P01 is reserved for master's programmes and other advanced training activities, with flexible teaching laboratories that can be reconfigured for lectures, workshops or group work. The upper floors P02–P04 host departmental, interdepartmental and excellence research centres, arranged in open-plan macro-spaces that can be subdivided or combined according to evolving research needs (Politecnico di Torino – Area Edilizia e Logistica, 2022). Across all levels, shared facilities such as the atrium, event and meeting spaces, refreshment area and underground car park support informal interaction, dissemination events and everyday operation of the complex.

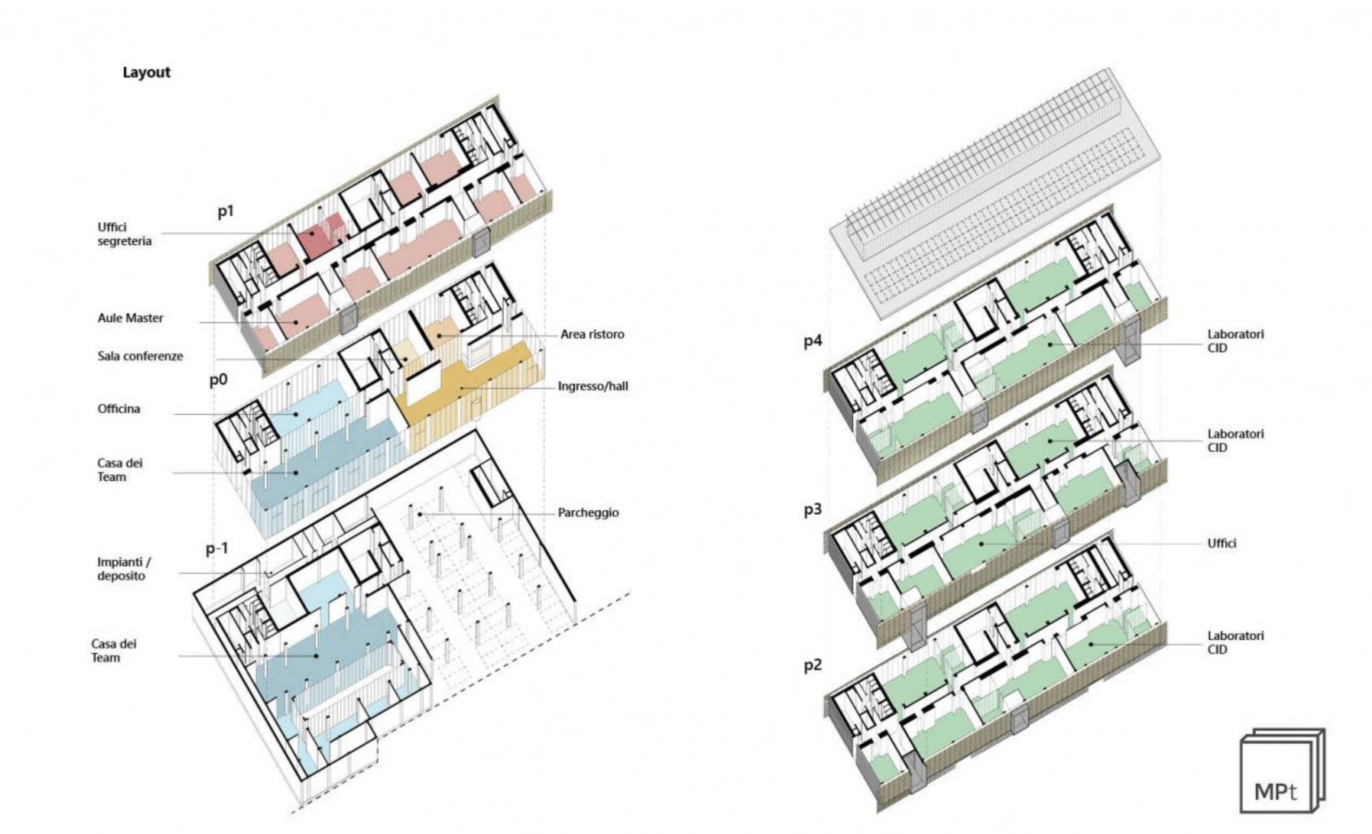


Figure 16. Functional distribution of DRH by floor (Casa dei Team, teaching spaces, offices and CID laboratories). Source: Politecnico di Torino, Masterplan – Digital Revolution House project page (2025).

From an environmental and technical standpoint, DRH comprises five levels above ground and one underground level and is designed and certified according to the ITACA Piemonte non-residential protocol. The project explicitly targets nearly-zero energy performance, reduced water consumption, the use of low-impact materials and high standards of indoor comfort. In this sense, Digital Revolution House is not only a container for research on digital transition and artificial intelligence, but also a demonstrator of sustainable campus architecture, intended to attract talent and partnerships while reinforcing the strategic role of the Politecnico campus within Turin's innovation landscape (Politecnico di Torino, 2025a, 2025b).

3.8.2 Urban and planning context

The Digital Revolution House (DRH) is located in Municipal District 3 (San Paolo–Cenisia–Pozzo Strada–Cit Turin), within the block delimited by Corso Ferrucci, Corso Vittorio Emanuele II, Via Paolo Borsellino and Via Vochieri. In the Municipal Master Plan (PRG) the area is classified as an Urban Transformation Zone (Zona Urbana di Trasformazione), identified as Ambito 8.18/1 Spina 2, a strategic sector where major urban restructuring is intended to support Turin's transition from an industrial city to a more diversified, innovation-oriented profile. Within this framework, the DRH plot forms part of Unità di Intervento 4, conventionally known as the "ex-Westinghouse area", historically owned by the City of Turin and progressively redeveloped through public–private partnerships (Politecnico di Torino – Area Edilizia e Logistica, 2022; Politecnico di Torino, n.d.).

More specifically, DRH completes the redevelopment of Area di Intervento 4B.1, where the Energy Centre—completed in 2016 and in use by the Politecnico since 2017—already occupies sub-area B.1, while sub-area B.2 hosts the Codegone university residences. The new building is conceived as a linear, five-storey volume with a double-loaded layout, aligned with the orientation of the plot and fronting onto Via Paolo Borsellino. It is positioned along the eastern boundary of the site at a minimum distance of 10 m from the former Nebiolo factory, while the space between DRH and the Energy Centre is organised as a through-garden with regular pedestrian paths connecting the two research facilities and opening visual relations towards the wider

Politecnico campus and the Lamarmora Garden. Before the intervention, the part of Area 4B.1 not occupied by the Energy Centre consisted largely of a roof garden above the underground car-park slab and a temporary surface car park, with only a small strip of true permeable green area (category Ab) (Politecnico di Torino – Area Edilizia e Logistica, 2022, 2023). DRH therefore plays a dual role: it consolidates the cluster of high-tech university facilities in the ex-Westinghouse area and at the same time redefines the open spaces between them as a permeable connection between campus and city.

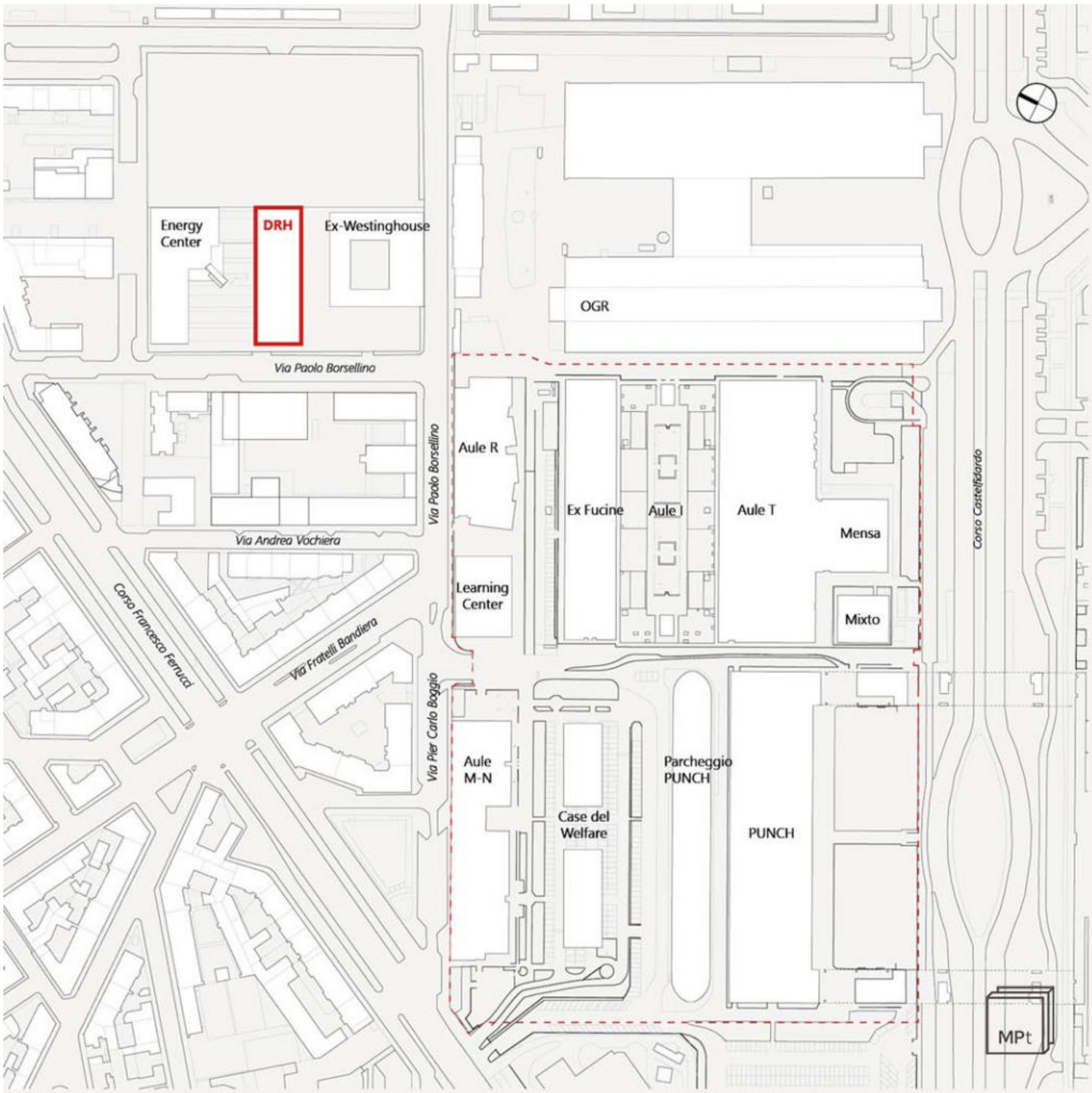


Figure 17. Territorial framework of the DRH within the Spina 2 area, along the technological and cultural axis linking the Politecnico Citadel, OGR and Energy Center (source: Politecnico di Torino, Digital Revolution House – Progetto esecutivo).

3.8.3 Environmental / energy concept and ITACA positioning

From an environmental perspective, the Digital Revolution House is conceived as a nearly zero-energy building (NZEB) in energy class A4. Electricity demand is largely covered by roof-mounted photovoltaic arrays, while heating and cooling are provided by a groundwater-based geothermal system feeding a polyvalent chiller/heat pump. Space conditioning relies predominantly on radiant emission systems operating with low-temperature water, thereby reducing electricity consumption for fluid pumping. Mechanical ventilation is ensured by air-handling units with high-efficiency heat recovery and variable-flow control; in summer these are complemented by free-cooling strategies and, where feasible, natural ventilation. The overall configuration is designed to minimise primary-energy demand and maximise the contribution of on-site renewable sources, in line with national NZEB requirements (Decree 26/06/2015; D.Lgs. 28/2011) (Politecnico di Torino – Area Edilizia e Logistica, 2022).

In parallel, the project is declared compliant with the Minimum Environmental Criteria (Criteri Ambientali Minimi – CAM, DM 11/10/2017), addressing not only energy performance but also water saving, indoor environmental quality, acoustic and thermal comfort, and the selection of construction products. Particular attention is given to the disassemblability of components, the use of recycled and renewable materials, and the control of hazardous substances.

The environmental strategy has been independently verified through certification under the Protocollo ITACA Regione Piemonte – Edifici non residenziali 2018. The validation sheet ITPM-NRES-004-2022-TO, issued on 31 May 2023, confirms an overall ITACA score of 2.3 for DRH and reports the project's performance for individual criteria (iiSBE Italia, 2023). Material- and circularity-related indicators show, for example, an 11% share of recycled/recovered materials (B.4.6 – Materiali riciclati/recuperati), a 3.4% share of materials from renewable sources (B.4.7 – Materiali da fonti rinnovabili), a high proportion of certified materials (B.4.11 – Materiali certificati) and the maximum score for operational solid-waste management (C.3.2 – Rifiuti solidi previsti in fase operativa). These results indicate that DRH has already undergone a detailed protocol-based assessment of its material composition, renewable and certified products and waste strategies.

3.8.4 Sustainability-critical stages of the DRH project

Project documentation for the Digital Revolution House highlights three main sustainability-critical stages in the life of the building: the operational phase, the construction phase and the interface with existing campus infrastructures (Politecnico di Torino – Area Edilizia e Logistica, 2022).

The operational stage is critical because the building's very low energy demand and NZEB profile depend on the correct functioning of a complex system of geothermal wells, heat pumps, radiant panels, high-efficiency ventilation and photovoltaic generation, all designed in accordance with CAM requirements. Long-term performance will be determined not only by the efficiency of these systems at commissioning, but also by their durability, maintenance regimes and eventual replacement cycles. In this sense, the proposed durability indicator directly engages with one of the main sustainability hotspots of DRH, by making visible the expected frequency of component renewal over the 50-year reference period.

The construction stage constitutes a second critical phase. The DRH is built in a constrained urban site above an existing underground car park and within an area affected by past industrial uses and potential contamination. The executive design therefore foresees extensive preliminary demolitions, UXO clearance, deep excavation retained by micropile "Berlin" walls, and strict procedures for the classification, separation and off-site management of excavated soils and construction waste in accordance with D.Lgs. 152/06 and DPR 120/2017. Although these processes lie largely outside the scope of the durability indicator, they frame the project in terms of resource use, soil management and the limits of on-site reuse, thereby reinforcing the need to reduce future replacement demand where possible.

A third sustainability-critical dimension concerns the interfaces with existing assets, particularly the Energy Center and its network of shared services. The Energy Center must remain fully operational during construction, and in the long term DRH will share several key infrastructures, including medium-voltage electricity supply, groundwater extraction and reinjection wells, district-heating connection, black- and storm-water systems, rainwater-reuse facilities and data and voice networks. This interdependence has implications for operational reliability, maintenance planning and resilience to future upgrades. It also emphasises the importance of robust, durable components in the shared systems and in the envelope and interior finishes of DRH, whose replacement cycles may affect not only the building itself but also the functioning of the wider campus cluster.

3.8.5 Documentation and inputs used

The main documentary basis for the durability and replacement-cycle indicator is the Relazione di Valutazione prepared for the Digital Revolution House (DRH) within the Protocollo ITACA Regione Piemonte – Edifici non residenziali 2018 (file: DHR-Relazione_di_Valutazione_prog-REV1). This report provides the complete ITACA scoring of the project and consolidates the key quantitative evidence used by the design team, including material inventories, energy balances, indoor-environment calculations and acoustic simulations, together with a structured list of supporting drawings and technical reports (Politecnico di Torino – Area Edilizia e Logistica, 2022). In this thesis it is adopted as the primary sustainability-assessment baseline against which the proposed durability indicator is positioned.

The Relazione di Valutazione is organised around a set of “base documents” and “supporting documents” (Documenti base and Documenti di supporto alla comprensione del progetto). For the purposes of this research, these are grouped into a limited number of document families that collectively provide:

1. the geometric and functional description of DRH.
2. the definition of envelope and construction systems.
3. the ITACA and CAM evidence on energy, materials and comfort; and
4. the quantitative data needed to estimate component areas and material masses.

Architectural drawings (plans, sections, façades and external-layout drawings) are used as "executive drawings for the indicator". They support the reconstruction of the functional and spatial organisation of the building, the distinction between zones with different usage profiles (Casa dei Team laboratories, advanced-training spaces, research offices, circulation and service areas) and the approximation of gross areas for each internal finish, floor build-up and ceiling type. Sections and façades are read together to locate loggias, double-height spaces, external shading structures and other façade articulations, and to assign envelope types and exposure conditions to specific durability classes.

Stratigraphy abaci and construction-detail drawings (e.g. AbacoStratigr and external-works layouts) are used to identify the layer build-ups and material types of roofs, façades, internal floor slabs, raised floors, partitions and external surfaces. In the ITACA evaluation these stratigraphies already underpin criteria related to permeable surfaces, mitigation of the urban-heat-island effect and CAM compliance. In this thesis they also provide the technical basis for defining component families in the durability analysis and for aligning qualitative durability classes with the same constructions used in the ITACA scoring.

ITACA, CAM and Legge 10 technical reports (including the NZEB/Legge 10 report and CAM compliance documentation) supply the broader sustainability context. The ITACA sheets report performance indices for energy-related criteria such as B1.3 (total primary energy), B3.2 (renewable energy for thermal uses), B3.3 (on-site electrical production), B6.1 and B6.2 (useful thermal energy for heating and cooling), together with their reference-building values. These are based on detailed EDILCLIMA-EC700 simulations and system descriptions, which are cited as attachments. The same model is used in the CAM/Legge 10 technical report to demonstrate compliance with national NZEB requirements and with the Minimum Environmental Criteria (Criteri Ambientali Minimi). Although these energy and CAM documents are not used directly in the durability calculations, they describe the expected operating conditions of DRH and confirm that the building has already been evaluated through a complete protocol-based framework, which the proposed indicator is intended to complement rather than replace.

The ITACA report also contains material-related and circularity-oriented criteria, notably B4.6 (Materiali riciclati/recuperati) and B4.7 (Materiali da fonti rinnovabili). For these criteria the design team compiled an inventory table of all building materials expressed in kilograms, from which the total mass of recycled/recovered materials and renewable-source materials is calculated. The resulting values (around 11% and 3.4% respectively) are supported by dedicated attachments (e.g. DRH-B4.6-Calcolo materiali riciclati-recuperati.pdf; DRH-B4.7-Calcolo peso materiali edificio.pdf) and by environmental product declarations and technical datasheets for specific products such as bamboo components and wood-based acoustic panels. This existing material inventory is particularly important for this thesis, because it can be cross-referenced with the component-based durability analysis and, in future work, coupled with environmental indicators for replacement-phase impacts.

A further group of documents comprises specialist reports on indoor environment and comfort. Criterion D2.5 (Ventilazione e qualità dell'aria interna) is supported by plans showing the main rooms to be verified and the aeraulic layouts, together with a dedicated calculation file. Criteria D3.1 and D3.3 (Comfort termico estivo/invernale) are based on the same EDILCLIMA model used for energy analysis, documented through an abacus of envelope elements, sections showing shading devices and a detailed calculation report. Acoustic criteria D5.5 and D5.6 refer to a specialist report on passive acoustic requirements and CAM-acoustics compliance. Collectively, these attachments formalise a functional and environmental zoning of the building that is consistent across energy, ventilation and acoustic analyses. This zoning is adopted here to differentiate usage classes in the durability assessment (e.g. intensively used teaching spaces, research offices, circulation, technical rooms) and to interpret the expected service conditions for interior finishes and acoustic linings.

Finally, quantity take-offs and cost documents (computo metrico estimativo and related spreadsheets, together with the material-mass attachments used for B4.6/B4.7) are used, where available, to validate or approximate surface areas and quantities for selected component families. This reduces the need for manual measurement on 2D drawings and increases consistency between the durability indicator and the ITACA baseline.

Table 6 summarises these document families and their role in the durability and replacement-cycle indicator.

Table 6. Main DRH document families used in the durability and replacement-cycle analysis

Document family	Typical examples (codes)	Main role in this thesis
Architectural drawings (plans, sections, façades, site plans)	Urban layout, floor plans S01–P05, main sections, façades	Define overall geometry, functional zoning and approximate areas of rooms, envelope elements and internal finishes; support allocation of component families and exposure conditions.
Stratigraphy abaci and construction details	Abacus of stratigraphies; external-works and parameter plans; façade details	Describe layer build-ups of roofs, façades, floors and partitions; align durability classes with the constructions already used in ITACA and CAM assessments.
ITACA evaluation report and CAM/Legge 10 technical reports	DHR-Relazione di Valutazione; CAM/Legge 10 technical report; NZEB certificates	Provide the overall sustainability baseline (energy, materials, comfort) against which the new indicator is positioned; confirm NZEB and CAM compliance and the

		existing treatment of circular-economy aspects.
Specialist energy, ventilation, comfort and acoustic reports	Ventilation and IAQ report; thermal-comfort report; acoustic-performance report; EDILCLIMA-EC700 outputs	upply functional and environmental zoning (by use and exposure); describe ventilation, comfort and acoustic strategies that influence expected service conditions and replacement cycles of internal components.
Quantity take-offs, material inventories and cost documents	Computo metrico estimativo; attachments B4.6 and B4.7 with total material masses	Provide quantitative data (areas, volumes, masses) for main component families; allow cross-checking of quantities used in the durability indicator and potential future coupling with environmental and cost analyses.

In addition to these project-specific documents, the durability and replacement-cycle indicator relies on external references for service-life assumptions. Numerical service-life values for each component family are not taken from the DRH project documentation but from:

- international standards on service-life planning, in particular the ISO 15686 series on buildings and constructed assets, which provide reference service lives and methodological guidance.
- technical guides and handbooks issued by national and international organisations (e.g. building-research institutes and professional bodies) that report indicative service lives for envelopes, finishes and building-services components under typical maintenance regimes.
- manufacturer documentation and product datasheets, consulted selectively where DRH specifications could be matched to standard product families (e.g. ventilated façades, acoustic panels, flooring systems); and
- informal input from Politecnico di Torino facility-management staff, where available, on expected replacement cycles in heavily used campus spaces.

These external sources are presented in greater detail in Chapter 6, where they are linked to individual component families in the DRH case study and systematically cited in the component-level tables in Appendix X.

Finally, it is worth noting that ITACA criterion E6.5 (Disponibilità della documentazione tecnica degli edifici) formally commits the Politecnico di Torino to archiving all key technical documents—general and specialist reports, maintenance plans and the as-built BIM model—at the offices of the Area Edilizia e Logistica (Politecnico di Torino – Area Edilizia e Logistica, 2022). This institutional commitment is particularly relevant for the durability indicator, which assumes that information on component stratigraphy, materials and replacement logic will remain accessible throughout the service life of the building.

3.8.6 Why DRH is an appropriate case study

The Digital Revolution House represents a particularly suitable case study for piloting the Durability & Replacement Cycles indicator. First, it is a recent project that has already undergone a complete sustainability assessment and external validation under the ITACA Regione Piemonte – Non-Residential Buildings 2018 protocol. This guarantees a high-quality, coherent documentary base, including a building-level material inventory, detailed stratigraphy abaci and a comprehensive set of technical reports and simulations. In addition, the commitment to archive the "as-built" BIM model and all key technical documents at the Politecnico di Torino ensures that information on components and replacement logic will remain accessible over the building life, which is a fundamental precondition for any service-life-oriented indicator.

Second, DRH exhibits the typical characteristics of contemporary university buildings: complex envelope systems, a wide variety of internal finishes and technical services, and an expected long design life under intensive patterns of use. These features make the building representative of the broader campus stock while also providing sufficient diversity in components and usage conditions to test the sensitivity of the indicator. Taken together, the recency, documentation quality and functional profile of DRH make it an appropriate and methodologically robust test bed for the proposed durability and replacement-cycle indicator, with results that can be plausibly generalised to other campus buildings.

3.9 Methodology for Identifying the Key SBTool Gap Indicator

3.9.1 Aim and overall approach

The present chapter shifts from describing SBTool's coverage to identifying, in a transparent and evidence-based manner, a single key gap indicator that warrants further development and testing.

The aim of this chapter is to systematically identify one CE-related gap indicator which:

1. meaningfully contributes to the sustainability performance of a university campus, and specifically of the Digital Revolution House (DRH); and
2. represents a genuine SBTool gap, either by addressing an issue not currently operationalised, or by strengthening a weakly defined criterion.

To ensure full academic rigour, the selection process integrates:

- a structured qualitative reassessment of each remaining indicator using a six-part evaluation template.
- expert input from a Delphi process (Round 2) to embed sector-wide consensus; and
- a quantitative weighting of evaluation criteria using the Analytic Hierarchy Process (AHP), ensuring consistent prioritisation among criteria such as measurability, stakeholder acceptance and policy alignment.

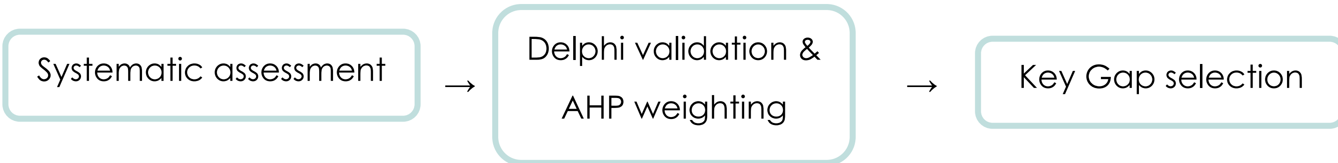


Figure 18. Indicator Extraction Procedure

3.9.2 Definition of a SBTool Gap Indicator

In this thesis, a SBTool gap indicator is not simply any construct that could refine existing KPIs, but a circular-economy (CE) indicator that exposes a structural weakness in the SBTool framework at category or issue level. Following the exclusions justified in the previous section, Criterion–Exact and Criterion–Partial indicators are no longer considered candidates, as they are either already fully operationalised or only require marginal KPI refinements within SBTool's current logic.

Instead, the focus is placed on indicators that are only partially represented at category or issue level, and whose underlying concept is explicitly CE-related (e.g. slowing, narrowing or closing loops; adaptability; recoverability). These indicators do not merely "add another metric" to an existing criterion but have the potential to:

- make a currently implicit CE mechanism explicitly visible in the SBTool structure; and
- support the formulation of a new or substantially strengthened category/issue rather than a minor adjustment to existing KPIs.

Within this study, an indicator is therefore treated as a SBTool gap only if it simultaneously meets two core requirements of this thesis more than the others:

1. it contributes meaningfully to the sustainability of a university campus, and,
2. it improves the existing SBTool by strengthening the representation of a relevant circular-economy issue.

Under this definition, the "gap" is understood as a missing or weak category/issue node in the SBTool CE structure that can be meaningfully filled by a CE indicator with demonstrable relevance for university campuses, rather than as a marginal optimisation of criteria that are already well established.

3.9.3 Evaluation framework and criteria

The conceptual definition of a SBTool gap indicator set out in Section 4.2 is operationalised through two high-level evaluation criteria. These criteria translate the abstract requirements of "campus sustainability contribution" and "SBTool improvement potential" into concrete questions that can be applied consistently to each candidate indicator. Together, they provide the backbone of the gap-identification methodology and guide the stepwise narrowing from several candidates to a single key gap indicator.

1.Contribution to University-Campus Sustainability

This criterion assesses whether an indicator has the potential to make a substantive difference to the sustainability performance of university buildings and, in particular, of the DRH case study. An indicator is considered strong under this dimension if it:

- addresses recurrent or structurally embedded challenges in campus estates, such as high refurbishment frequency, intensive use patterns, complex technical systems or long service lives of key components.
- can be directly connected to design, renovation, operation or maintenance decisions taken by campus managers, facility teams and designers, rather than remaining at the level of abstract environmental accounting.
- is applicable to the DRH and, by extension, to comparable university buildings, based on information that can realistically be obtained from design documentation, asset registers or standard management practices; and

- is expected to influence performance over a significant portion of the life cycle (e.g. through altered replacement cycles, improved adaptability or reduced material throughput), rather than only in rare or exceptional situations.

Under this criterion, indicators that merely provide additional descriptive detail without informing actual campus decision-making are downgraded in favour of indicators that can support concrete choices about how buildings are designed, refurbished and managed.

2. Potential for SBTool Improvement

The second criterion examines how far an indicator can strengthen the SBTool framework at the category/issue level, in line with the definition of a gap adopted in this thesis. An indicator is considered strong under this dimension if it:

- reveals a missing or weak node in the SBTool CE structure at category or issue level, rather than suggesting only a marginal KPI refinement within an already well-defined criterion.
- enables the explicit operationalisation of a CE construct that is currently only mentioned qualitatively, implicitly or in fragmented form (e.g. adaptability, recoverability, reversibility, reuse or disassembly capacity).
- can be integrated into SBTool/ITACA without contradicting its overall assessment logic, by lending itself to clear scoring rules, thresholds and documentation requirements; and
- has the potential to be generalised beyond the DRH case study and applied to other university buildings, thereby improving the robustness and comparability of SBTool-based assessments for the university sector.

In combination, these two evaluation criteria ensure that the selected key gap indicator is not only theoretically aligned with circular-economy principles, but also practically relevant for university campuses and capable of driving a meaningful enhancement of the SBTool framework at the structural (category/issue) level.

3. Six Operational Evaluation Criteria

To translate the two overarching dimensions defined in Sections 4.3.1 and 4.3.2 into a set of operational criteria that can be applied to individual indicators, six evaluation criteria were formulated on the basis of the literature on sustainability indicators, circular-economy assessment in the built environment and multi-criteria decision-making in green building protocols. This initial criteria set was subsequently submitted to expert critique and refinement through the Delphi process described in Section 4.4.1 and was later weighted using the AHP procedure presented in Section 4.4.2.

The six criteria are defined as follows:

- **Measurability & Data Availability**

This criterion considers whether an indicator can realistically be calculated with the data that universities already have or can easily collect. International guidelines for sustainable development and circular economy monitoring stress that indicators should be not only relevant, but also measurable with regularly available and reliable data (Joint UNECE/Eurostat/OECD Task Force on Measuring Sustainable Development, 2013; OECD, 2024). In practical terms, this means that the metric needs a clear definition, a recognised way of being calculated, and inputs that are likely to be found in design documents, asset registers or institutional databases. Environmental indicator studies also show that, especially in data-driven approaches, data availability is a key filter when selecting indicators (Niemeijer, 2002; Niemeijer & de Groot, 2008). In this thesis, indicators that can be quantified using standard campus data sources therefore score higher on Measurability & Data Availability than those that would require very specialised measurements or new, resource-intensive data collection.

- **Stakeholder Acceptance**

This criterion considers how likely it is that the main campus actors (facility managers, technical staff, designers and decision-makers) will understand, accept and actually use the indicator in practice. Several authors underline that indicators are only effective if they are seen as legitimate and meaningful by the people who work with them, not just technically correct on paper (Bell & Morse, 2008; Gunnarsdottir et al., 2020). Circular-economy monitoring guidelines also include “acceptance” or “stakeholder relevance” as a basic quality of good indicators, alongside relevance, credibility and ease of monitoring (European Environment Agency, 2020; Platform for Accelerating the Circular Economy, 2021). In this thesis, indicators that can be explained in simple terms to campus stakeholders and that are likely to be perceived as fair and useful score higher on Stakeholder Acceptance than indicators that are difficult to interpret, politically sensitive or disconnected from everyday campus decisions.

- **Policy/Market & Territorial Alignment**

This criterion considers whether an indicator is consistent with the main policy frameworks, regulatory targets and market signals that shape decisions on university buildings in Italy and in the wider European context. International guidelines on sustainability and green-economy indicators emphasise that indicators should be directly linked to current policy priorities and monitoring needs, rather than being designed in isolation from the policy context (OECD, 2024; Partnership for Action on Green Economy [PAGE], 2020; Pintér et al., 2012). Experience with adapting SBTool to different countries also shows that indicators need to reflect national regulations, climatic conditions and sector-specific priorities if they are to be meaningful at territorial scale (Saraiva et al., 2019). In this thesis, indicators that clearly support Italian and European circular-economy agendas and can inform real campus planning and investment decisions therefore score higher on Policy/Market & Territorial Alignment than those that are only loosely connected to existing policy and market frameworks.

- **Circularity Impact**

This criterion evaluates the degree to which an indicator captures mechanisms that slow, narrow or close resource loops over the building life cycle. Recent guidance on circular-economy statistics stresses that indicators should not only track environmental pressures but also describe how material flows are kept in circulation through reuse, high-quality recycling and circular business models (United Nations Economic Commission for Europe & Organization for Economic Co-operation and Development, 2024; OECD, 2024). Principles for circular-economy monitoring, such as the Bellagio Declaration, likewise emphasize the need to follow changes along the whole material life cycle rather than focusing solely on end-of-pipe emissions (European Environment Agency, 2020). In the built environment, reports and case-study collections show how strategies such as durability, design for adaptability, reversible construction and high-value reuse of components can deliver strong circularity outcomes by extending service life and reducing demand for virgin materials (Barner et al., 2024; Circle Economy & Realdania, 2025). In this thesis, indicators that directly influence material flows, service life, adaptability, reuse, deconstruction or similar circular levers in long-lived campus buildings therefore score higher on Circularity Impact than indicators that only provide generic environmental performance information without explicitly reflecting loop dynamics.

- **Integration Feasibility & Essentiality**

This criterion considers both how easily a candidate indicator can be integrated into the existing SBTool/ITACA structure and how essential it is for representing a specific circular-economy aspect that is currently weak or missing. From an integration perspective, indicator development literature stresses the importance of designing indicators so that they fit coherently within existing assessment frameworks, avoid overlaps and double counting, and remain compatible with established scoring and aggregation procedures (Pülzl et al., 2012; Corrêa Hackenhaar et al., 2024). In practice, this means that the indicator should be compatible with SBTool's hierarchy of issues, categories, criteria and indicators, and should be normalisable and aggregable using the same basic logic already applied in SBTool/ITACA (Moro et al., 2023; CESBA MED, 2019). At the same time, recent frameworks for sustainability indicator selection emphasise that new indicators should not be added simply because they are technically possible, but because they bring essential information that is not yet captured by the current set and that supports clearer decision-making (Abbasi et al., 2023). In this thesis, indicators score higher on Integration Feasibility & Essentiality when they can be incorporated into existing SBTool slots without disrupting the scoring system, while at the same time filling a clearly identifiable circular-economy gap rather than duplicating the intent of existing criteria.

- **Evidence Strength**

This criterion considers how robust the conceptual and empirical basis of a candidate indicator is. International guidance on sustainability and circular-economy monitoring stresses that indicators should be analytically sound and built on clear theoretical foundations and reliable methods, rather than being ad-hoc constructs (OECD, 2024; Pintér et al., 2012). Indicator development studies likewise argue that good indicators balance theory and practice, drawing on established scientific knowledge and, where possible, on previous applications in real assessment contexts (Pülzl et al., 2012). In related fields, reviews of sustainability and energy indicators evaluate indicator sets partly on whether they are comprehensive, robust and tested in practice, rather than only proposed conceptually (Gunnarsdottir et al., 2020). Similarly, work on eco-innovation indices highlights that composite indices and their underlying indicators must rest on a transparent conceptual model and data that allow meaningful interpretation of scores and trends (Park et al., 2017). In this thesis, indicators with a broad and consistent supporting literature, precedent use in building or campus assessments and, where available, empirical links to environmental or circular outcomes therefore score higher on Evidence Strength than indicators backed by sparse or highly speculative evidence.

Together, these six criteria operationalise the two high-level dimensions defined earlier: Contribution to University-Campus Sustainability and Potential for SBTool Improvement. Measurability & Data Availability, Stakeholder Acceptance and Policy/Market & Territorial Alignment primarily relate to the feasibility and institutional relevance of applying an indicator in real campus contexts, whereas Circularity Impact, Integration Feasibility & Essentiality and Evidence Strength focus more directly on the indicator's capacity to enhance the SBTool framework and to represent CE mechanisms in a robust way. These criteria set provides the analytical backbone for the Delphi validation (Section 4.4.1), the AHP weighting (Section 4.4.2) and the subsequent comparison of candidate gap indicators in the stepwise selection procedure.

3.9.4 Scoring scale for the six criteria (1–5)

For all indicators, the six evaluation criteria are scored on a five-point ordinal scale. The scale is defined as follows.

Measurability & Data Availability

5 – Indicator can be fully calculated for typical campus buildings using data that are already standard. No additional data collection is needed.

4 – Indicator can be calculated with mostly standard data, plus some limited additional assumptions or simple data collection.

3 – Indicator requires several non-standard data sources or approximations but is still feasible with reasonable effort.

2 – Indicator requires detailed or rarely available data that are only present in some projects.

1 – Indicator requires data that are generally unavailable or would be too costly to collect systematically.

Stakeholder Acceptance

5 – The concept is widely known and already used by campus managers, technical offices and designers; very easy to explain and perceived as clearly useful.

4 – The concept is understandable and likely to be accepted after a short explanation; it links directly to familiar decisions.

3 – The concept is somewhat abstract or new but can be explained; some stakeholders may see it as useful, others as "extra work".

2 – The concept is difficult to explain or is perceived as only marginally relevant to day-to-day decisions.

1 – The concept is very technical or remote; most stakeholders would not understand or accept it as a basis for assessment.

Policy/Market & Territorial Alignment

5 – Indicator is directly reflected in current EU and Italian policy requirements, voluntary schemes or market practices for buildings, and is clearly relevant for university campuses.

4 – Indicator is consistent with existing policies and market trends (e.g. EU frameworks, national guidelines, sectoral strategies), even if not yet mandatory for campuses.

3 – Indicator is broadly compatible with policy goals but only indirectly mentioned or weakly connected to existing regulations or market instruments.

2 – Indicator is only marginally linked to current policy debates or market signals in the Italian/EU context.

1 – Indicator has no clear connection to existing policies, standards or market practices.

Circularity Impact

5 – Indicator strongly affects slowing, narrowing or closing loops over the building life cycle (e.g. major influence on service life, reuse potential or recovery of components).

4 – Indicator has a clear and non-negligible influence on material flows or circular strategies, even if focused on specific elements or stages.

3 – Indicator has some connection to circularity, but the effect on actual loop performance is moderate or indirect.

2 – Indicator is only weakly linked to circularity and mainly reflects generic environmental performance.

1 – Indicator has no meaningful link to circular resource loops.

Integration Feasibility & Essentiality

5 – Indicator can be integrated into SBTool/ITACA with minimal adaptation and clearly fills an essential gap at category/issue level, without double counting existing criteria.

4 – Indicator fits reasonably well into the current structure and adds important, but not absolutely critical, information.

3 – Indicator can be integrated but requires some adjustments in scoring or structure and only moderately improves the existing framework.

2 – Indicator is difficult to fit into the current slots or risks overlapping with several existing criteria.

1 – Indicator is very hard to integrate without major restructuring of SBTool/ITACA.

Evidence Strength

5 – Indicator is supported by a solid conceptual basis and multiple empirical applications in buildings or campuses, with clear links to environmental or circular outcomes.

4 – Indicator is well grounded in the literature and has some precedent applications, even if not yet widely used.

3 – Indicator has a reasonable conceptual basis but limited empirical testing or application in practice.

2 – Indicator is mainly conceptual, with sparse or early-stage evidence.

1 – Indicator is speculative and lacks a clear supporting literature.

3.9.5 Delphi procedure for validating the evaluation criteria

To avoid arbitrary or researcher-driven decisions, the detailed assessment stage integrates two complementary decision-support methods:

Delphi Method – Validation of Evaluation Criteria

The Delphi exercise was designed to ensure that the criteria used to evaluate candidate gap indicators were conceptually sound and not arbitrarily defined by the researcher. Rather than asking experts to select a gap indicator directly, the Delphi rounds focused on critiquing and refining the evaluation criteria that would later be applied in the stepwise selection procedure.

Panel and purpose

A purposive panel of six experts was assembled by the supervisor, all with experience in building sustainability assessment and circular economy in the built environment. The overarching objective communicated to the panel was to strengthen the validity of the criteria used to prioritise SBTool gaps for university campuses, by assessing both their substantive relevance and the clarity of their definitions.

Rounds and survey administration

Two Delphi rounds were implemented using the Typeform online survey platform. In both rounds, experts received an email invitation containing: (i) the goal of the study and the specific purpose of the Delphi exercise; (ii) a short description of the SBTool gap concept adopted in the thesis; and (iii) detailed definitions of each proposed evaluation criterion and the type of gaps they were intended to capture. The email and the introductory text of the survey emphasised that the experts were invited to critique the criteria, not to endorse them uncritically. All responses were submitted online and processed anonymously. In Round 1 all six invited experts participated; in Round 2 four experts from the original panel completed the refined survey.

3.9.6 AHP procedure for weighting criteria

To translate the six validated criteria into quantitative weights, the Analytic Hierarchy Process (AHP) was applied. AHP is a multi-criteria decision-making method that derives relative weights from pairwise comparisons on a ratio scale and is widely used in sustainability and planning studies (Saaty, 1980, 2008). In this thesis, AHP was implemented using the web-based AHP Priority Calculator (AHP-OS) developed by Goepel, which computes eigenvector-based weights and consistency diagnostics for decision matrices (Goepel, 2013). The six criteria defined in previous section (Measurability & Data Availability, Stakeholder Acceptance, Policy/Market & Territorial Alignment, Circularity Impact, Integration Feasibility & Essentiality, and Evidence Strength) were entered as the elements of a 6×6 pairwise comparison matrix.

The pairwise judgements in the AHP matrix were not made independently of the Delphi exercise but were derived from the Round-2 relevance scores. For each criterion, the mean and median relevance ratings reported by the Typeform survey were inspected to obtain an overall ranking and to identify groups of criteria with similar importance. When two criteria showed very similar Delphi scores (means and medians close and overlapping distributions), they were treated as equally important in the AHP matrix and assigned a value of 1. When one criterion had clearly higher Delphi scores, but still in a comparable range, it was judged slightly to moderately more important and assigned a value of 3 on Saaty’s 1–9 scale. In cases where the Delphi results consistently favoured one criterion over another (higher mean and median, lower dispersion), a value of 5 was used to express stronger importance. The reciprocal values (1/3, 1/5) were used when the direction of comparison was reversed. Because the Delphi relevance scores for all six criteria were relatively close, only the values 1, 3 and 5 (and their reciprocals) were needed; more extreme values such as 7 or 9 were not used.

3.9.7 Stepwise selection procedure

Finally, a stepwise selection procedure was defined to narrow the set of candidate indicators. Starting from the pool of Category-Partial and Issue-Partial indicators retained after the cross-mapping exercise, the procedure applied the following steps: (i) an initial conceptual screening of remained indicators to exclude those that only extend environmental impact coverage without activating distinct CE mechanisms; (ii) a second screening to retain only those that embody genuinely circular-economy constructs aligned with the thesis aims; and (iii) a detailed scoring of the shortlisted indicators against the six criteria using the rubric and AHP weights described above. The empirical results of this procedure are reported in chapter 4.

3.10 Indicator Validation Procedure

To ensure the robustness and scientific rigour of the proposed metric, a multi-stage validation procedure was integrated into the research design. This process moved from theoretical validation to operational verification, ensuring that the selected indicator was not only conceptually sound but also practically applicable within the specific constraints of a university campus. The validation followed three distinct stages:

Stage 1: Expert Consensus on Evaluation Criteria (Content Validity) Before the key indicator was selected, the criteria used to identify it were subjected to expert scrutiny through the Delphi method described in Section 3.9.5. This phase ensured content validity, it confirmed that the parameters used to filter and prioritise potential indicators (such as measurability, stakeholder acceptance, and policy alignment) were representative of the actual needs of the sector and not arbitrarily defined by the researcher. By refining these criteria through iterative expert feedback, the selection process itself was validated against professional consensus.

Stage 2: Consistency of Decision Weights (Construct Validity) Once the criteria were established, their relative importance was weighted using the Analytic Hierarchy Process (AHP). This stage ensured construct validity by mathematically verifying the consistency of the decision-making logic. The AHP method includes an internal consistency ratio (CR) check, which flags contradictory judgements. Achieving a CR below the standard threshold (typically 10%) served as a quantitative validation that the prioritisation of the indicator was based on a coherent and logical set of preferences.

Stage 3: Feasibility Pilot on Case Study (Operational Validity) The final stage involved testing the indicator on a real-world pilot project (the Digital Revolution House) to verify its operational validity. This "validation by application" tested whether the theoretical definition of the indicator could survive contact with real project documentation. The pilot was designed to answer three critical questions:

1. Data Availability: Can the required inputs be found in standard regulatory documents (e.g., Legge 10 reports) without requiring expensive new data collection?
2. Granularity: Is the indicator sensitive enough to distinguish between different technological solutions (e.g., between distinct envelope systems)?
3. Workflow Feasibility: Can the calculation be performed using standard office tools (e.g., spreadsheets) within a reasonable timeframe?

Positive confirmation across these three stages constitutes the formal validation of the proposed approach, demonstrating that it is theoretically grounded, logically selected, and practically implementable.

Chapter 4. Results

4.1 Results of Classification with CircularB COST

A total of 53 building-scale CE/sustainability indicators were extracted and coded using the CircularB COST template. Each indicator was classified once per axis using the closed list adopted in this thesis (single primary class; secondary tags recorded only when the source was explicit). Verbatim fields (name, definition, unit) were locked and were not altered during coding.

Results are presented across the CircularB axes used in this thesis.

4.1.1 System scale

Indicators span the full range from material level through component/element/system to whole-building assessments. This mix enables both granular evaluation (e.g., material composition or component reusability) and portfolio-level benchmarking. The table below reports the distribution to support later SBTool mapping and to avoid double counting across scales.

Table 7. Distribution by system scale (N = 53)

Class	n	%	Notes for interpretation
Material level	20	37.7 %	A strong micro-scale subset encompasses qualities like recycle content and impact. They are excellent feeders for LCA modules; however, grouping rules need to be applied cautiously within SBTool to prevent double counting as data is rolled up to greater scales.
Component / Product / Element / System	24	45.3%	The most granular level facilitates DfD/DfA analysis and design module selections. These factors are excellent candidates to improve the criteria scoring adaptability, maintainability, and replaceability within SBTool.

Class	n	%	Notes for interpretation
Whole-building level	30	56.6%	The greatest whole-scale level correlates well with the Area Issue Criterion structure within SBTool and facilitates portfolio-wide benchmarking; however, data needs to be integrated while maintaining connections to smaller-scale data to ensure tracing.

Percentages are calculated over the 53 unique indicators. Indicators can operate at multiple scales, therefore totals exceed 100%.

4.1.2 Sustainability linkage

Coding assigns each of the 53 indicators to one or, where relevant, two sustainability pillars (Environmental, Economic, Social). In the summary table, n reports how many indicators are linked to each pillar at least once (primary or secondary). Percentages are calculated over the full indicator set (N = 53), so totals exceed 100% because some indicators carry multiple linkages.

Table 8. Distribution by sustainability linkage (occurrence basis, N = 53)

Class	n	%	Notes for interpretation
Environmental	47	88.7%	Dominant coverage reflects the maturity of LCA and resource/energy accounting (energy, carbon, resources, waste, water). These indicators already align closely with SBTool's existing structure; most require at most editorial alignment (units, EN-module boundaries, thresholds).
Economic	11	20.8%	Present but secondary. Items concentrate in LCC, procurement/logistics costs, and value retention. They often serve as enablers for environmental goals rather than a fully independent pillar; operational KPIs (€/t, €/m², route-cost benchmarks) and scoring bands would strengthen this strand in SBTool.
Social	4	7.5%	Marginal representation. Comfort, equity, and user well-being are under-specified in the CE literature reviewed. This is a priority growth area for SBTool—especially in campus settings where user impact is central (accessibility,

Class	n	%	Notes for interpretation
			inclusivity, health/comfort).

4.1.3 Primary life-cycle stage

Each of the 53 indicators was coded against the life-cycle stage(s) explicitly targeted by its source (no inference when the stage was not stated; an "Unspecified" category was used sparingly). The counts in Table below therefore report how many indicators are applicable to each stage at least once. Percentages are calculated over the full indicator set (N = 53); because several indicators span multiple life-cycle stages, the percentages do not sum to 100%.

Table 9. Distribution by primary life-cycle stage (N = 53)

Class	n	%	Notes for interpretation
Inception / Predesign	13	24.5%	Early levers are present but limited. Strengthening upfront decision support (e.g., circular briefs, target setting, option screening) would materially improve SBTool's influence before major impacts are locked in.
Design	36	67.9%	Largest cluster. Emphasis on LCA, material selection, and DfD/DfA mirrors current toolchains and data availability; SBTool can capitalize immediately here through consistent units, EN-module boundaries, and clear scoring bands.
Procurement	8	15.1%	Under-represented. Expanding circular procurement (spec clauses, SPP adoption, recycled/reused content requirements, take-back agreements) is a priority to translate design intent into contracted performance.
Construction	28	52.8%	Substantial presence in site practices, waste, equipment/logistics. These are prime candidates for operationalization (KPIs, data owners, evidence rules) so SBTool can assess quality of implementation.

Class	n	%	Notes for interpretation
Operation & Maintenance	18	34.0%	A reasonable base of use-phase performance (energy/water and routine maintenance). These metrics anchor longitudinal improvement on campuses; ensure metering/monitoring conventions are explicit.
Refurbishment / Adaptive reuse	15	28.3%	Mid-life transformation is visible and aligned with circularity aims. SBTool can better link refurbishment with functional-obsolescence risk and DfD readiness to avoid premature replacement.
End-of-life	35	66.0%	Strong coverage of deconstruction/reuse/recovery. Boundary rules must be explicit (EN 15978 modules C/D) to enable credible loop accounting and comparability across projects.

4.1.4 Level of quantification

Each indicator was coded by measurement depth as Quantitative, Semi-quantitative (anchored ordinal scales), or Qualitative (structured checklists). Coding was done at the indicator level (N = 53); no multi-coding was applied on this axis.

Table 10. Distribution by level of quantification (N = 53)

Class	n	%	Notes for interpretation
Quantitative	48	90.6%	Predominantly numeric indicators with explicit units/equations (e.g., kg CO_2e/m^2, $kWh/m^2 \cdot yr$, €/t). This profile is ideal for SBTool scoring and benchmarking, provided units are normalized, EN-module boundaries are stated, and threshold bands are defined.
Semi-quantitative	4	7.5%	Anchored rubrics (A–D; 0–3) capture expert judgement where evidence is observable but not fully numeric. These can be integrated into SBTool by defining clear anchors, audit evidence (what must be shown), and conversion bands to the scale.

Class	n	%	Notes for interpretation
Qualitative	1	1.9%	A structured checklist with defined criteria. If retained, it should be tied to auditable documentation and—where feasible—converted to a semi-quantitative rubric (e.g., counting satisfied items with minimum evidence).

4.1.5 Descriptive context (building use; developer type)

Tables 0.10 and 0-11, do not affect the SBTool crosswalk; they document transferability and provenance.

Building use (multi-label coverage)

Each of the 53 indicators was coded against all building-use classes explicitly addressed by its source. The counts therefore report how many indicators are applicable to each class at least once, and percentages are calculated over the full indicator set (N = 53); totals exceed 100% because some indicators span multiple building uses.

Table 11. Building use referenced in the source (N = 53)

Class	n	%
General / Unidentified	34	64.2%

Class	n	%
Residential	18	34.0%
Commercial	4	7.5%
Healthcare	-	0.0%
Industrial	2	3.8%
Heritage / Cultural	-	0.0%
Institutional (incl. campus)	1	1.9%
Mixed-use	5	9.4%

Interpretation:

The corpus skews general/unidentified (≈64.2%), which supports transfer across campus asset types but requires project-specific functional units and boundary notes. Residential forms a substantial minority (≈34%); commercial, industrial, and mixed-use are present but thin. Institutional/campus occurs rarely (≈1.9%), and healthcare/heritage are absent—useful gaps to address when tailoring SBTool criteria for laboratories, teaching facilities, and cultural assets.

Table 12. Developer type of the indicator (N = 53)

Class	n	%
Academia / Research	53	100.0%

Class	n	%
Government	-	-
NGO / Community / International	-	-
Industry / Consultancy	-	-

Note: NGO / international collaborators are mentioned in two of the reviewed papers, but only as partners rather than as primary developers of the indicators; accordingly, they are not coded as separate source classes in the table.

Interpretation: As shown in Table above, all 53 indicators (100%) originate from academia and research institutions, while no indicator has a government, NGO/community, or industry/consultancy source as its primary provenance. This homogeneous academic origin supports methodological rigor and conceptual coherence, but it also signals a lack of direct input from policymakers, practitioners, and community actors. To strengthen implementability and real-world uptake, subsequent work should pilot these KPIs with non-academic stakeholders and align them with relevant policy, regulatory, and market frameworks.

4.1.6 Consideration of contextual factors

This subsection reports the contextualization tag assigned to each indicator (single primary tag per indicator).

Table 13. Contextualisation of indicators (N = 53)

Context tag	n	%	Note for interpretation
Local/Regional	10	18.9%	A meaningful minority is tied to specific codes/markets; these will require localisation notes (benchmarks, factors)

Context tag	n	%	Note for interpretation
			in the SBTool annex to ensure fair scoring.
Global	43	81.1%	The majority are presented in a generally applicable form, which facilitates integration into SBTool with only minor editorial alignment.

4.1.7 Development methodology (provenance)

This subsection lists the methodological provenance tags recorded per indicator. Multiple tags may be present for a single indicator.

Table 14. Reported development methodology (N = 53; multiple tags possible)

Method tag	n	%
Literature review & content analysis	43	81.1%
Based on previous tool/indicator	28	52.8%
Surveys & questionnaires	3	5.7%
Interviews & focus groups	1	1.9%
Empirical data & case studies	31	58.5%
Simulation models & LCA scenarios	44	83.0%
Building codes & regulatory frameworks	24	45.3%

Method tag	n	%
Digital tools	24	45.3%
Testing & validation	49	92.5%

Percentages rounded to one decimal place. Totals are >100% because each indicator can carry multiple methodological tags.

Interpretation:

-High incidence of testing/validation, literature/content analysis, and simulation/LCA scenarios, alongside substantial empirical/case evidence, indicates a robust methodological base suitable for operational scoring.

-Digital tools and explicit standards/regulatory references support replicability and auditability within SBTool workflows.

-Continuity with established metrics is strong ("based on previous tool/indicator"), easing calibration against existing SBTool criteria.

-Surveys and interviews are rare; where social or governance aspects are introduced, additional stakeholder validation may be required.

Taken together, the 53 indicators form a solid, mostly numeric evidence base. They cluster around design and end-of-life decisions, with decent coverage of construction and building operation, but they say far less about procurement and the social dimension of sustainability. Most are framed as globally applicable and originate in academic work—useful for methodological clarity, though they will need light localization and pilot testing when brought into SBTool/ITACA-Campus. In short, the set is ready for criterion-level cross-mapping and gap tagging, and it clearly points to where SBTool can gain the most: stronger social metrics, clearer procurement levers, and a few sharper tools for the earliest project stages.

4.2 Results of Cross-Walk to SBTool (Exact/Partial/Gaps)

4.2.1 Table reading guide:

- Criterion (Exact): an SBTool indicator already exists with the same construct and commensurate unit/boundary → adopt/align.
- Issue/Category/Criterion (Partial): the concept is present in SBTool, but a measurable KPI, unit, or boundary is missing/misaligned → operationalise (define method/threshold).

This arrangement provides a transparent, replicable bridge from the literature corpus to SBTool implementation. System boundaries for each indicator were assigned using EN 15978/EN 15804 life-cycle modules (A1–A3, A4–A5, B1–B7, C1–C4, D). Indicators related to design-for-disassembly were scoped against Level(s) 2.4 (Design for deconstruction) and then qualitatively checked against ISO 20887 to ensure alignment with recognized DfD/A principles.

4.2.2 Cross-Mapping Matrix

Table 15 lists each indicator with its Paper ID(s), SBTool mapping status and slot, and the paired circular tags (10R strategy; Loop).

Table 15. Cross-mapping of literature-derived indicators to SBTool and Circular Economy classes.

Indicator	Paper IDs	SBTool level	SBTool slot Issue → Category → Criterion	10R (primary)	Loop
1. Life Cycle GHG Emissions Assessment (LCA-GHG)	187	Criterion (Partial)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow

Indicator	Paper IDs	SBTool level	SBTool slot Issue → Category → Criterion	10R (primary)	Loop
2. Eco-Efficiency Indicator (thermal vs. emissions)	187	Criterion (Partial)	A. Energy A2. Energy Efficiency	Reduce	Narrow
3. Use of Supplementary Cementitious Materials (SCMs)	187	Criterion (Partial)	C. Resource Management C3. Materials Management C3.2 & C3.1	Reduce (Recycle)	Narrow (Close)
4. Durability & Replacement Cycles	187	Category (Partial)	E. Service Quality E2. Optimization and Maintenance	Repair/Refurbish	Slow
5. Recycled Biogenic Components	187	Criterion (Partial)	C. Resource Management C3. Materials Management C3.2, C3.3	Recycle	Close
6. Carbon Footprint GWP	188/221	Criterion (Partial)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
7. Reclaimed Components Substitution Rate	188	Criterion (Partial)	C. Resource C3. Materials Management C3.4 Design for deconstruction	Reuse	Close
8. Global Warming Potential (GWP)	189	Criterion (Partial)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
9. Fossil Resource Scarcity	189	Category (Partial)	A. Energy A2. Energy Efficiency/A3. Renewable Energy	Reduce	Narrow
10. Embodied Energy (EN1)	189	Criterion (Partial)	A. Energy A2. Energy Efficiency A2.2 Embodied non-renewable primary energy	Reduce	Narrow
11. LCC for Formwork Materials	189	Criterion (Partial)	F. Economy F1. Life-Cycle Cost	Reduce	Narrow
12. GWP for Reused Components	190	Criterion (Partial)	A. Energy A1. GHG Emissions	Reuse (Reduce)	Close (Narrow)
13. Global Warming Potential (GWP)	201/222	Criterion (Exact)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
14. Recycling Potential	201	Criterion (Exact)	C. Resource Management C3: Materials Management C3.2 Recycled materials	Recycle	Close

Indicator	Paper IDs	SBTool level	SBTool slot Issue → Category → Criterion	10R (primary)	Loop
15. Acidification Potential (AP)	201	Issue (Partial)	A. Energy / C. Resource Management	Reduce	Narrow
16. Primary Energy Input – Non-Renewable (PENRT)	201	Criterion (Partial)	A. Energy A2. Energy Efficiency A2.2 Embodied non-renewable primary energy	Reduce	Narrow
17. Effectiveness of Pre-Deconstruction Audit	206	Category (Partial)	C. Resource Management C3. SBTool Materials Management C3.4 Design for deconstruction	Reuse/Recycle	Close
18. Recycling Route Cost Comparison (DEc4)	206	Criterion (Partial)	F. Economy F1 Life-Cycle Cost	Recycle	Close
19. GHG Emissions from Waste Transport (DE2)	206	Criterion (Partial)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Recycle/Recover	Narrow/Close
20. Material Composition Indicators (MCIs)	210	Criterion (Partial)	C. Resource Management C3. SBTool Materials Management	Reduce	Narrow
21. Deconstructability Score (D-score)	217	Criterion (Partial)	C. Resource Management C3. SBTool Materials Management C3.4 Design for deconstruction	Reuse (Refurbish)	Close (Slow)
22. Recovery Score (R-score)	217	Criterion (Partial)	C. Resource Management C3. SBTool Materials Management C3.4 Design for deconstruction	Recover/Recycle	Close
23. Environmental Score (E-score)	217	Issue (Partial)	A. Energy / C. Resource Management	Reduce	Narrow
24. Energy Demand for Heating (E1)	221	Criterion (Exact)	A. Energy A2. Energy Efficiency A2.6 Heating Need	Reduce	Narrow
25. Energy Demand for Cooling (E2)	221	Criterion (Exact)	A. Energy A2. Energy Efficiency A2.7 Cooling Need	Reduce	Narrow
26. Embodied Energy (EN1)	221	Criterion (Exact)	A. Energy A2. Energy Efficiency A2.2 Embodied non-renewable primary energy	Reduce	Narrow
27. Final Energy Requirement (E3)	221	Criterion (Partial)	A. Energy A2. Energy Efficiency	Reduce	Narrow
28. Electricity Production from PV	221	Criterion (Exact)	A. Energy A3. Renewable Energy A3.1 Share of renewable energy	Rethink	Narrow

Indicator	Paper IDs	SBTool level	SBTool slot Issue → Category → Criterion	10R (primary)	Loop
(E4)			on-site, relative to total final energy consumption for building operations		
29. Rainwater & Greywater Use (EN3)	221	Criterion (Exact)	C. Resource Management C2. Water Management C2.4 & C2.5	Reuse/Recover	Close
30. Daylight Factor, DF300 (IC1)	221	Criterion (Exact)	B. Environmental Quality B4 Lighting and Visual Comfort B4.1 Daylight	— (not CE-specific)	—
31. Universal Design Accessibility (S1)	221	Criterion (Exact)	E. Service Quality E3. Design for All E3.1 Universal access on site and within the building	— (social)	—
32. Abiotic Resource Depletion Potential (ADP-elements)	222	Issue (Partial)	A. Energy +C. Resource Management	Reduce	Narrow
33. Climate Footprint (CF)	548	Criterion (Partial)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
34. Material Footprint (MF)	548	Criterion (Partial)	C. Resource Management C3 Materials Management	Reduce	Narrow
35. Water Footprint (WF)	548	Criterion (Partial)	C. Resource Management C2. Water Management	Reduce	Narrow
36. Energy Footprint (EF)	548	Criterion (Partial)	A. Energy A2.2 Embodied non-renewable Primary Energy	Reduce	Narrow
37. Recycled Aggregate Content (%) (RAC)	548	Criterion (Exact)	C. Resource Management C3. Materials Management C3.2 Recycled materials	Recycle	Close
38. Zero Waste Index (ZWI)	550	Criterion (Partial)	C. Resource Management C1. Waste Management	Reduce/Recycle	Narrow/Close
39. Waste Reduction Potential (WRP)	550	Criterion (Partial)	C. Resource Management C1. Waste Management	Reduce	Narrow
40. Substitution Potential for Materials (SPM)	550	Criterion (Partial)	C. Resource Management C3. Materials Management	Recycle/Reuse	Close
41. Reuse Rate for Components (RR)	552	Criterion (Partial)	C. Resource Management C3. Materials Management C3.4 Design for deconstruction	Reuse	Close
42. Environmental Point	552	Issue	A. Energy / C. Resource	Reduce	Narrow

Indicator	Paper IDs	SBTool level	SBTool slot Issue → Category → Criterion	10R (primary)	Loop
Score (ReCiPe)		(Partial)	Management		
43. Construction Complexity	552	Criterion (Partial)	C. Resource Management C3. Materials Management C3.4 Design for deconstruction	Reuse/Refurbish	Slow/Close
44. CO2 Emissions	558	Criterion (Partial)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
45. Energy Consumption of Production	558	Criterion (Partial)	A. Energy A2 Energy Efficiency A2.2 Embodied non-renewable primary energy	Reduce	Narrow
46. New Product to Wood Residue Ratio (MDF)	558	Criterion (Partial)	C. Resource Management C3. Materials Management	Recycle	Close
47. Product market price (€/tonne)	558	Category (Partial)	F. Economy	not CE-mechanism specific	-
48. CO_2eq Emissions per m^2 of Demolished Area	564	Criterion (Partial)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Recycle/Recover	Close/Narrow
49. Reusability Index (RI)	564	Criterion (Partial)	C. Resource Management C3. Materials Management C3.4 Design for deconstruction	Reuse	Close
50. CO_2eq Emissions from Machinery Use	564	Criterion (Partial)	A. Energy A1. GHG Emissions	Reduce	Narrow
51. Rate of Reusable vs Recyclable Steel	564	Criterion (Partial)	C. Resource Management C3. Materials Management	Reuse/Recycle	Close

Table Index:

- Criterion (Exact)
- Criterion (Partial)
- Category (Partial)
- Issue (Partial)

Table 16. Counts by Issue and Mapping Status (N = 51, duplicated indicators did not count.)

Issue	Criterion-Exact		Criterion-Partial		Category-Partial		Issue-Partial		Total
	N	%	N	%	N	%	N	%	
A. Energy	6	54.5%	12	40.0%	1	25%	4	50%	45.1%
B. Environmental Quality	1	9.1%	0	-	0	-	0	-	2.0%
C. Resource Management	3	27.3%	16	53.3%	1	25%	4	50%	47.1%
E. Service Quality	1	9.1%	0	-	1	25%	0	-	3.9%
F. Economy	0	-	2	6.7%	1	25%	0	-	5.9%
Total	21.6%		58.8%		7.8%		7.8%		

Note. All Issue–Partial indicators are cross-cutting and relate simultaneously to both Issue A (Energy) and Issue C (Resource Management). For this cross-tabulation they are therefore recorded in both rows, so the sum of Issue–Partial counts by Issue (n = 8) exceeds the number of distinct Issue–Partial indicators (n = 4). The "Total" row reports unique indicator counts (N = 51).

The table cross-tabulates the 51 unique indicators against SBTool Areas (A–F) and four levels of correspondence (Criterion-Exact, Criterion-Partial, Category-Partial, Issue-Partial). For each Area, the values in the interior columns (N and %) report how many mappings fall under that correspondence level and what share they represent of all mappings in that level. For example, of the 11 Criterion-Exact mappings, 54.5% are associated with A. Energy and 27.3% with C. Resource Management; similarly, 53.3% of all Criterion-Partial mappings fall under C. Resource Management and 40.0% under A. Energy.

The "Total" column summarizes coverage at the indicator level: it shows, for each

Area, the percentage of the 51 indicators that are linked to that Area by at least one mapping, irrespective of the correspondence level. On this basis, 45.1% of the indicators relate to A. Energy and 47.1% to C. Resource Management, whereas B. Environmental Quality, E. Service Quality and F. Economy account for 2.0%, 3.9% and 5.9% of the indicator set, respectively. Because several indicators map to more than one Area and/or appear at more than one correspondence level, the column totals across Areas and across correspondence levels exceed 100%. All four Issue-Partial indicators are cross-cutting between A. Energy and C. Resource Management, which explains the 50%–50% split in that column despite their relatively small share (7.8%) of the overall indicator set.

SBTool cross-mapping interpretation:

The mapping results show that 21.6% of the 51 indicators have a Criterion-Exact counterpart in SBTool, while 58.8% are Criterion-Partial. This means that just over one fifth of the indicators can be transferred almost directly into SBTool criteria, whereas the majority already correspond to an existing SBTool issue and category but diverge in the exact formulation of the criterion (e.g. KPI definition, unit, boundary, or scoring rule). A further 7.8% of the indicators are only Category-Partial and another 7.8% are Issue-Partial, i.e. SBTool currently reflects only the broader thematic category or issue without a fully aligned criterion. Because some indicators exhibit more than one type of correspondence, these percentages overlap and do not sum to 100%. In the next step, the indicators are therefore grouped into four sets according to their degree of alignment with SBTool (Criterion-Exact, Criterion-Partial, Category-Partial, Issue-Partial); this structuring makes the subsequent evaluation more manageable and provides a transparent pathway to identify the key gap indicator.

Looking at the distribution by Area, approximately 45.1% of the indicators relate to A. Energy and 47.1% to C. Resource Management, confirming that these two Areas dominate the CE-related content of the reviewed literature. In contrast, B.

Environmental Quality accounts for only 2.0% of the indicators, E. Service Quality for 3.9% and F. Economy for 5.9%. Within the mapping, 54.5% of all Criterion-Exact mappings fall under A. Energy and 27.3% under C. Resource Management, while Criterion-Partial mappings are primarily associated with C. Resource Management (53.3%) and A. Energy (40.0%). Category-Partial indicators are evenly distributed across A. Energy, C. Resource Management, E. Service Quality and F. Economy (25% each), whereas all Issue-Partial mappings are split evenly between A. Energy and C. Resource Management (50%–50%), reflecting their cross-cutting nature.

From a broader perspective, this pattern suggests that, in the reviewed literature, energy and resource management are by far the most intensively developed CE-related issues, while environmental quality, service quality and economic aspects receive comparatively little attention. SBTool, in turn, already recognises a wide range of CE-related issues across Areas A–F, but many of them are only partially operationalised into precise criteria and KPIs. This supports the identification of potential gaps in SBTool: either existing issues that require more detailed, CE-oriented criteria, or additional circularly relevant issues/categories that should be strengthened. In the following stage of the thesis, each indicator—starting from its four-fold grouping—will be evaluated individually to determine which ones most effectively contribute to the sustainability performance of the selected university campus case study, thereby converging on the key gap indicator to be further developed and tested.

4.2.3 Criterion (Exact) Indicators evaluation:

Table 17. Criterion-Exact Indicators

Criterion (Exact) Indicators	**KPI in SBTool**	**SBTool slot (Issue →Category→ Criterion)**	**10R (primary)**	**Loop**
1. Global Warming Potential (GWP)	kg CO_2-eq/m² over 50 years	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
2. Embodied Energy	MJ (or kWh) per m²	A. Energy A2. Energy Efficiency A2.2 Embodied non-renewable primary energy	Reduce	Narrow
3. Energy Demand for Heating (E1)	kWh/m²·year	A. Energy A2. Energy Efficiency A2.6 Heating Need	Reduce	Narrow
4. Energy Demand for Cooling (E2)	kWh/m²·year	A. Energy A2. Energy Efficiency A2.7 Cooling Need	Reduce	Narrow
5. Renewable Energy Share	%	A. Energy A3. Renewable Energy A3.1 Share of renewable energy on-site, relative to total final energy consumption for building operations	Rethink/Reduce	Narrow
6. Electricity Production from PV (E4)	%	A. Energy A3. Renewable Energy A3.1 Share of renewable energy on-site, relative to total final energy consumption for building operations	Rethink	Narrow
7. Daylight Factor, DF300 (IC1)	%	B. Environmental Quality B4 Lighting and Visual Comfort B4.1 Daylight	— (not CE-specific)	
8. Rainwater & Greywater Use (EN3)	%	C. Resource Management C2. Water Management C2.4 & C2.5	Reuse/Recover	Close
9. Recycling Potential	%	C. Resource Management C3: Materials Management C3.2 Recycled materials	Recycle	Close
10. Recycled Aggregate Content (%) (RAC)	%	C. Resource Management C3. Materials Management C3.2 Recycled materials	Recycle	Close
11. Universal Design Accessibility (S1)	Score	E. Service Quality E3. Design for All E3.1 Universal access on site and within the building	— (social)	

According to the results of the SBTool cross mapping table 11 indicators are exactly covered in SBTool. Therefore, they will not be considered in the next steps of gap identification.

4.2.4 Criterion (Partial) Indicators evaluation:

Table 18. Criterion-Partial Indicators

Criterion (Partial) Indicators	KPI	SBTool slot (Issue →Category→ Criterion)	10R (primary)	Loop
1. GWP for Reused Components	kg CO_2-eq/m² GFA	A. Energy A1. GHG Emissions	Reuse (Reduce)	Close (Narrow)
2. Life Cycle GHG Emissions Assessment (LCA-GHG)	kg CO_2-eq/m² wall (50-year service life)	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
3. CO_2eq Emissions from Machinery Use	t CO_2eq	A. Energy A1. GHG Emissions	Reduce	Narrow
4. Global Warming Potential (GWP)	kg CO_2-eq per m² of component	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
5. GHG Emissions from Waste Transport (DE2)	kg CO_2-eq	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Recycle/Recover	Narrow/Close
6. CO_2eq Emissions per m² of Demolished Area	kg CO_2eq/m²	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Recycle/Recover	Close/Narrow
7. Climate Footprint (CF)	kg CO_2-eq/m² GFA	A. Energy A1. GHG Emissions A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years	Reduce	Narrow
52. Carbon Footprint	kg CO_2-eq/m²	A. Energy A1. GHG Emissions	Reduce	Narrow

Criterion (Partial) Indicators	KPI	SBTool slot (Issue →Category→ Criterion)	10R (primary)	Loop
GWP	GWP of roof truss $kgCO_2-eq/truss, A1–A3$	A1.1. CO_2 equivalent emissions per useful internal floor area for a period of 50 years		
8. Eco-Efficiency Indicator (thermal vs. emissions)	$kgCO_2$-eq/m²	A. Energy A2. Energy Efficiency	Reduce	Narrow
9. Final Energy Requirement (E3)	kWh/m²·year	A. Energy A2. Energy Efficiency	Reduce	Narrow
10. Primary Energy Input – Non-Renewable (PENRT)	[GJ] per building / component	A. Energy A2. Energy Efficiency A2.2 Embodied non-renewable primary energy	Reduce	Narrow
11. Embodied Energy (EN1)	MJ (non-renewable primary energy)	A. Energy A2. Energy Efficiency A2.2 Embodied non-renewable primary energy	Reduce	Narrow
12. Zero Waste Index (ZWI)	%	C. Resource Management C1. Waste Management	Reduce/Recycle	Narrow/Close
13. Waste Reduction Potential (WRP)	%	C. Resource Management C1. Waste Management	Reduce	Narrow
14. Water Footprint (WF)	m³ H_2O-eq/FU (AWARE WU)	C. Resource Management C2. Water Management	Reduce	Narrow
15. Use of Supplementary Cementitious Materials (SCMs)	%	C. Resource Management C3. Materials Management C3.2 & C3.1	Reduce (Recycle)	Narrow (Close)
16. Recycled Biogenic Components	%	C. Resource Management C3. Materials Management C3.2, C3.3	Recycle	Close
17. Reclaimed Components Substitution Rate	%	C. Resource C3. Materials Management C3.4 Design for deconstruction	Reuse	Close
18. Material Composition Indicators (MCIs)	kg/m²	C. Resource Management C3. SBTool Materials Management	Reduce	Narrow
19. Deconstructability Score (D-score)	dimensionless score (0–1)	C. Resource Management C3. SBTool Materials Management C3.4 Design for deconstruction	Reuse (Refurbish)	Close (Slow)
20. Recovery Score (R-	dimensionless score	C. Resource Management C3. SBTool Materials	Recover/Recycle	Close

Criterion (Partial) Indicators	KPI	SBTool slot (Issue →Category→ Criterion)	10R (primary)	Loop
score)	(0–1)/ %	Management C3.4 Design for deconstruction		
21. Material Footprint (MF)	kg or t per FU (1 m³ concrete or 1 m² GFA)	C. Resource Management C3 Materials Management	Reduce	Narrow
22. Substitution Potential for Materials (SPM)	kg or tones	C. Resource Management C3. Materials Management	Recycle/Reuse	Close
23. Reuse Rate for Components (RR)	%	C. Resource Management C3. Materials Management C3.4 Design for deconstruction	Reuse	Close
24. Construction Complexity	Dimensionless	C. Resource Management C3. Materials Management C3.4 Design for deconstruction	Reuse/Refurbish	Slow/Close
25. New Product to Wood Residue Ratio (MDF)	%	C. Resource Management C3. Materials Management	Recycle	Close
26. Reusability Index (RI)	%	C. Resource Management C3. Materials Management C3.4 Design for deconstruction	Reuse	Close
27. Rate of Reusable vs Recyclable Steel	%	C. Resource Management C3. Materials Management	Reuse/Recycle	Close
28. LCC for Formwork Materials	$/FU	F. Economy F1. Life-Cycle Cost	Reduce	Narrow
29. Recycling Route Cost Comparison (DEc4)	€/t	F. Economy F1 Life-Cycle Cost	Recycle	Close
30. Energy Footprint (EF)	MJ/m 2	A. Energy	Reduce	Narrow

According to extracted indicators which they in the criterion section are partially included in the SBTool, even though no KPI defined for these indicators but almost all of them can be expressed as subsets or refinements of existing SBTool KPIs. For each indicator, the mapping table identifies whether an underlying SBTool KPI already exists and clarifies how the partial indicator could be derived from, or layered on top of, that KPI. In this sense, the "partial" label does not mean that SBTool cannot measure these aspects at all, but rather that they are not yet operationalized as separate criteria with their own scoring scales and remain embedded inside broader issues.

Here each indicator justified one by one for mapping as a criterion partial in the SBTool slot:

CO_2 Emissions
In Vamza et al. (2021), "CO_2 emissions" is defined as the greenhouse-gas emissions arising from the production process of 1 metric ton of product, with data in kg CO_2/t for MDF, particleboard, mycelium insulation and solid fuel alternatives.
This matches SBTool A1.1 CO_2-eq emissions in terms of impact category but not in functional unit (SBTool uses kg CO_2-eq per m² useful floor area over 50 years). Therefore, it is best classified as Criterion–Partial under A1. GHG Emissions, with KPI recorded as kg CO_2eq per tonne of product (kg CO_2/t), potentially convertible to building-level LCA (kg CO_2eq/m²) if scaled.

Global Warming Potential (GWP)
In Tighnavard Balasbaneh et al. (2024), Global Warming Potential (GWP) is used to compare four reusable wall formwork systems (plastic, steel, plywood, timber) in a cradle-to-cradle LCA. The indicator measures the total life-cycle CO_2-equivalent emissions of each formwork option, calculated in SimaPro using Ecoinvent factors and expressed as kg CO_2-eq per 10.8 m² of concrete wall (3.0 × 3.6 m) for both 1 use and 50 reuse cycles. The assessment includes production and manufacturing, transport, and end-of-life stages with recycling credits, and results are reported as total GWP per formwork configuration. Conceptually, this indicator addresses the same construct as SBTool A1.1 "CO_2-equivalent emissions per useful internal floor area for a period of 50 years", namely the global warming impact of construction materials. However, its functional unit and system boundary differ from the SBTool KPI: in the paper, GWP is a component-level total (kg CO_2-eq per formwork system / per 10.8 m² wall over a given number of uses), not a whole-building GWP normalised per m² of useful floor area over a 50-year reference period with predefined scoring bands. To use it in SBTool, additional steps would be required. Because it aligns with the criterion intent but not with SBTool's exact KPI formulation and functional unit.

Life Cycle GHG Emissions Assessment (LCA-GHG)
In Paiva et al. (2022), the Life Cycle GHG Emissions Assessment (LCA-GHG) quantifies the greenhouse gas emissions of alternative plastering systems (earth mortars with bamboo particles vs. conventional cement–lime mortars). The study follows EN 15978/EN 15804 in a cradle-to-grave scope, including stages A1–A4, B1, B4, C2 and C4, and defines the functional unit as a "wall (in m²) with a service life of 50 years

covered with 5 cm of mortar (2.5 cm on each side)". Results are expressed as kg CO_2-eq per m² of wall over 50 years for each mortar option.
This indicator clearly addresses the same environmental construct as SBTool A1.1 "CO_2-equivalent emissions per useful internal floor area for a period of 50 years", using a comparable 50-year time horizon and GWP100 metric. However, its functional unit and system boundary are defined at component level, i.e. per m² of plastered wall rather than per m² of useful internal floor area of the whole building, and only the plastering system is modelled, not the complete building. To be used within SBTool A1.1 it would first need to be upscaled and renormalised to building floor area. For this reason, LCA-GHG in this paper is considered Criterion–Partial under A1.1: it matches the criterion's intent and impact category, but not its exact KPI formulation or building-level functional unit.

Carbon Footprint GWP

-In Sadowski (2021), the carbon footprint of materials (EN2) expresses the embodied carbon of construction materials in the student-housing design variants, i.e. the GWP associated with the material supply chain only. It is calculated with Athena Impact Estimator and reported as kg CO_2-eq/m² of building area, with results grouped into performance bands (A–D: 0–500, 500–1000, 1000–2000, >2000 kg CO_2-eq/m²). Although this indicator uses the same core metric as SBTool A1.1 (GWP in kg CO_2-eq/m²), its life-cycle scope and reference frame are narrower: EN2 covers only embodied emissions of materials, without explicitly modelling a 50-year reference period or integrating operational stages, and the outcome is mapped to a bespoke A–D scale rather than to SBTool's scoring thresholds. For these reasons, the correspondence with SBTool A1.1 is limited to the level of criterion intent, and EN2 is therefore classified as Criterion–Partial, rather than Criterion–Exact.
-In Tomczak et al. (2023), GWP quantifies the global warming potential of timber roof-truss elements under different reuse-matching algorithms, with the assessment restricted to the structural elements of the roof rather than the whole building. GWP is obtained by multiplying the volume of each timber element by an emission factor for new sawn timber (28.9 kg CO_2-eq/m³) and summing the contributions of reused and new elements to derive the total impact in kg CO_2-eq for each truss configuration; performance is then reported as the percentage reduction in GWP relative to an all-new baseline. Although this indicator uses the same impact category as SBTool A1.1 (GWP, kg CO_2-eq), its functional unit and scope differ substantially: it is defined at component level (roof truss) rather than per useful internal floor area, and the life-cycle boundary is essentially cradle-to-gate (A1–A3) with no 50-year reference period. Because the environmental construct aligns but the unit, scale and system boundary are narrower than those prescribed for SBTool A1.1, the correspondence is limited to the level of criterion intent, and the indicator is therefore classified as Criterion–Partial, rather than Criterion–Exact.

Energy Consumption of Production – 558

"Energy consumption of production" is defined as the energy use during the production of 1 metric ton of product, reported in MWh/t in the MCA data matrix for the four recycling alternatives.

This corresponds to SBTool A2.2 Embodied non-renewable primary energy in terms of construct (embodied energy) but again differs in functional unit and system boundary (product-level vs building-level per m² over 50 years). It should therefore be treated as Criterion–Partial under A2. Energy Efficiency, with KPI MWh per tonne of product (MWh/t), and only indirectly translatable to the SBTool KPI (MJ or kWh/m²).

Climate Footprint (CF)

In Mostert et al. (2021), Climate Footprint (CF) is the product climate footprint, computed as Global Warming Impact (GWI) with GWP100 and expressed in kg CO_2-eq per functional unit (1 t RA concrete, 1 m³ concrete, and finally 1 m² GFA of the concrete structure).

Conceptually this matches SBTool A1.1 "CO_2-eq emissions per useful internal floor area", but the scope is narrower: it only includes A1–A3 and C1–C3 for the structural concrete, not the whole building and not the full 50-year life cycle. For this reason, it is classified as Criterion (Partial) under A1.1 (Reduce, Narrow).

GWP for Reused Components

In De Wolf et al. (2020), GWP for Reused Components is operationalised as the global warming potential of the K.118 building when its components are reused, calculated by LCA over embodied life-cycle stages (A1–A5, B1–B5, C1–C4, D) and expressed per gross floor area in kg CO_2-eq/m² for different allocation methods and life-cycle positions (first / intermediate / last use).

It is mapped to A1. GHG Emissions (Reuse/Reduce – Close/Narrow) because it directly quantifies how reusing components changes the building's embodied GHG profile, i.e. emission reductions and closed material loops compared to new materials. However, it is rated Criterion (Partial) rather than Criterion–Exact since it excludes operational energy stages B6–B7, while SBTool A1 typically refers to total 50-year GWP per floor area. Moreover, it compares several alternative allocation formulas instead of defining a single, normative SBTool KPI and scoring rule.

CO_2eq Emissions from Machinery Use

The indicator in Melella et al. (2021) isolates the greenhouse-gas impact of construction/demolition equipment such as excavators, power tools, and trucks used for connection removal, demolition of slabs and walls, and on-site transport. For each activity, the study first estimates operating times for each machine type (e.g. hours of excavator use, minutes of power tools), then multiplies these by fuel or electricity emission factors to obtain total CO_2eq emissions attributable to machinery. Results are reported as tonnes of CO_2eq (t CO_2eq) per demolition scenario and can be

normalised to a functional unit (e.g. per m² of floor area or per m² of demolished surface) in line with EN 15978 practice.
Within SBTool, this indicator is closest to A. Energy → A1. GHG Emissions, but it focuses specifically on construction/demolition logistics rather than on operational energy or cradle-to-grave embodied emissions. Using A1.1 CO_2eq per m² over 50 years as a reference, it is academically defensible to propose the same normalised unit (kg CO_2eq/m²) for machinery emissions, so they can be integrated or compared on the same building-area basis. Because SBTool does not currently separate machinery-related CO_2eq as a dedicated criterion.

GHG Emissions from Waste Transport (DE2)
In Jiménez-Rivero & García-Navarro (2016), GHG Emissions from Waste Transport (DE2) measures the difference in CO_2-equivalent emissions between sending gypsum waste to recycling versus landfilling. KPI for this indicator is kg CO_2-eq (additional or avoided GHG emissions from transporting the building's gypsum waste to recycling instead of landfill (project/building deconstruction scale).
It matches the intent and scope of SBTool A1.1 (GHG emissions associated with the building's life cycle, specifically EoL waste logistics for one building/material stream) but it is not expressed as "CO_2-eq per useful internal floor area over 50 years"; it is a stage-specific, material-specific transport indicator, not a full building 50-year GWP normalised by m². It therefore aligns conceptually with A1.1 but requires reformulation (normalisation by floor area and integration into the 50-year horizon) to be used as the exact SBTool KPI → hence Criterion (Partial).

CO_2eq Emissions per m² of Demolished Area
In Melella et al. (2021) introduce CO_2eq emissions per m² of demolished area to characterise the climate impact of demolition operations for different structural systems. After quantifying the operating time of tools and machinery used to demolish slabs and walls, and multiplying by fuel type–specific emission factors, the authors calculate total demolition-stage emissions and then normalize them by the demolished surface area. For example, the Avenida Central Building generates 1.42 kg CO_2eq/m², whereas the Melopee school generates 2.16 kg CO_2eq/m² of demolished surface, highlighting how thicker, in-situ concrete floors drive higher demolition-related GHG emissions. The KPI is therefore clearly defined as kg CO_2eq per m² of demolished area (kg CO_2eq/m²).
In SBTool, this indicator fits best under Energy → GHG Emissions→ CO_2 equivalent emissions per useful internal floor area for a period of 50 years, which is mapped as a Criterion-Partial extension of the A1 GHG Emissions logic. SBTool's existing KPI A1.1 already uses kg CO_2eq/m² over 50 years for the whole life cycle; adapting the same normalised form to the demolition stage is methodologically consistent but not explicitly codified in the current protocol. For this reason, CO_2eq per m² demolished is treated as a Criterion-Partial indicator: it shares the same unit structure and

performance construct as SBTool's operational GHG criterion but applies it specifically to end-of-life demolition scenarios, which SBTool currently does not quantify in a stand-alone way.

Eco-Efficiency Indicator (thermal vs. emissions)

In Paiva et al. (2022), the Eco-Efficiency Indicator (thermal vs. emissions) is defined as the ratio between life cycle GHG emissions of each earth-mortar option and its thermal resistance R for a 5 cm plaster layer. The KPI is a composite index "kgCO_2-eq/m² per unit of thermal resistance", where lower values mean better eco-efficiency (more thermal performance per unit embodied emissions).

It is mapped to SBTool A. Energy → A2. Energy Efficiency (Reduce, Narrow) because it links envelope thermal performance to reduced climate impact but classified as Criterion (Partial) since it is a component-level, study-specific ratio rather than the standard building-level energy KPIs (annual final/primary energy in kWh/m²·yr) used in SBTool.

Final Energy Requirement (E3)

In Sadowski (2021), Final Energy Requirement (E3) is calculated for each student housing design as the simulated annual final energy demand per unit floor area, using Sefaira, and expressed in kWh/m²·year with performance bands A–D (A: 0–60, B: 60–80, C: 80–100, D: >100 kWh/m²·y).

It is mapped to A. Energy – A2. Energy Efficiency – Reduce/Narrow because it directly measures operational energy performance at whole-building level, aligned with SBTool's intent for energy-efficiency criteria. However, it is classified as Criterion (Partial) rather than Criterion–Exact since the categorisation (A–D thresholds and studio-specific benchmarking) does not coincide with SBTool's prescribed scoring scales and regulatory references.

So, it matches the same objective and scale as SBTool A2 (reducing operational energy demand) but not its exact metric and scoring framework, hence "Criterion (Partial)".

Zero Waste Index (ZWI)

In Sujai and Juwana (2021), the Zero Waste Index (ZWI) is defined as a composite index of waste reduction and recovery performance for Hotel XYZ's room-service solid waste. The KPI is the ZWI value (dimensionless index 0–1, often expressed as % of recoverable waste); in the case study, ZWI = 0.67, meaning 67 % of the waste can be recovered and substitute virgin materials/energy.

It is mapped to C. Resource Management – C1. Waste Management – Reduce/Recycle (Narrow/Close) because it quantifies how much operational waste is prevented from final disposal via recovery pathways. It is classified as Criterion (Partial) because, although the scope and target match SBTool C1, the KPI form (index with substitution factors, no m²-normalisation or SBTool threshold bands) differs from SBTool's standard C1 metrics (kg/m²·year, % mass diverted), so it cannot be directly used as a Criterion-Exact SBTool indicator without reformulation.

Primary Energy Input – Non-Renewable (PENRT)

In Schützenhofer et al. (2022), PENRT is derived from a component-based life cycle assessment of the ski lodge using the EI3 framework. For each building element and construction product, the authors quantify the non-renewable primary energy required over the life cycle and report PENRT as an absolute value in gigajoules [GJ] at component level, subsequently aggregated to a total for the whole building. In other words, the indicator measures the total non-renewable primary energy demand associated with the construction scenario, without normalisation by floor area or reference service life.

Conceptually, this indicator corresponds to SBTool criterion A2.2 "Embodied non-renewable primary energy", since it addresses the same construct (embodied non-renewable primary energy of building materials and components). However, the functional unit and formulation differ from SBTool's KPI, which is defined as non-renewable primary energy per useful internal floor area over a 50-year reference period (MJ or kWh/m² over 50 years, with defined scoring bands). In the paper, PENRT remains an absolute building/component total in GJ, with no m² normalisation and no explicit 50-year index or SBTool-compatible scoring scheme. Because the indicator cannot be used directly as the SBTool KPI without additional transformation (normalisation by floor area and alignment of the time horizon and thresholds), its alignment is limited to the level of criterion intent, and it is therefore classified as Criterion–Partial under A2.2, rather than Criterion–Exact.

Waste Reduction Potential (WRP)

In Sujai and Juwana (2021), Waste Reduction Potential (WRP) is operationalised through the Zero Waste Index (ZWI), defined as the ratio between the amount of waste managed by recovery options (recycling, composting, etc.), weighted by substitution factors, and the total waste generated ($\Sigma\ WMS_i \cdot SF_i\ /\ \Sigma\ GWS$). In the Hotel XYZ case, ZWI = 0.67, meaning 67% of room-service solid waste can potentially be recovered to substitute virgin materials, energy and associated impacts. The KPI is therefore the ZWI value (0–1), often expressed as a percentage (%) of recoverable waste.

It is mapped as C. Resource Management – C1. Waste Management – Reduce/Narrow, Criterion (Partial) because it clearly targets waste minimisation and recovery in a single hotel (building-operations scale), but its index-based form and substitution-factor method differ from SBTool's standard C1 KPIs (typically kg/m²·year and % diverted with fixed threshold bands). It therefore aligns with the criterion's intent but cannot be directly used as an SBTool KPI without reformulation, justifying the Criterion (Partial) classification.

Embodied Energy (EN1)

In Tighnavard Balasbaneh et al. (2024), Embodied Energy (EN1) is used to compare four reusable wall formwork systems (plastic, steel, plywood and timber) within a cradle-to-cradle LCA. The indicator is quantified as the cumulative non-renewable primary energy demand associated with each formwork option, calculated using the Cumulative Energy Demand (CED) method and Ecoinvent data in SimaPro. Results are first expressed in MJ/kg of material and then aggregated to give the total embodied energy in MJ for the full formwork configuration required to cast a 3.0 × 3.6 m concrete wall (10.8 m^2) over 1 and 50 use cycles, including production, transport and end-of-life credits for recycling and energy recovery.

Conceptually, this indicator addresses the same construct as SBTool A2.2 "Embodied non-renewable primary energy", namely the primary energy associated with construction materials. However, its functional unit and boundary differ from the SBTool KPI, which is defined as non-renewable primary energy per useful internal floor area over a reference service life (MJ or kWh/m^2 for the whole building). In the paper, EN1 remains a component-level total (MJ per formwork system / per 1 m^2 of wall for a given number of reuses), without normalisation to building floor area or integration into a 50-year building life and SBTool scoring bands. Because it aligns with the criterion's intent but not with its exact KPI formulation and functional unit, Embodied Energy (EN1) from this study is classified as Criterion–Partial under A2.2, rather than Criterion–Exact.

Water Footprint (WF)

In Mostert et al. (2021), the Water Footprint is calculated as a product water-scarcity footprint using the AWARE (water-scarcity characterization method) method and reported as Water Use (WU) in cubic meters per functional unit (1 t of recycled aggregate, 1 m^3 of concrete, or 1 m^2 GFA). The KPI is therefore the total AWARE water footprint per FU and the relative reduction (%) when substituting natural aggregates with recycled concrete. This aligns with SBTool C. Resource Management – C2. Water Management (Reduce, Narrow) because it measures life-cycle water consumption linked to material choices, but it is only Criterion (Partial) since SBTool does not explicitly use AWARE-based scarcity metrics or define building-level water-footprint thresholds.

Use of Supplementary Cementitious Materials (SCMs)

In Paiva et al. (2022), Use of Supplementary Cementitious Materials (SCMs) refers to the partial replacement of Portland cement in the earth-based mortar binder by fly ash (FA) and metakaolin (MK), with fixed mix proportions expressed in kg/m^3 of mortar (e.g. 46.17 kg/m^3 CPV, 50.79 kg/m^3 FA, 46.17 kg/m^3 MK).

The operative KPI implicit in the study is therefore the mass fraction of SCMs in the binder, i.e. FA+MK as a percentage of total cementitious binder mass (or, equivalently, kg SCM per m^3 of mortar), which is then propagated through the LCA to quantify GHG reductions relative to conventional cement–lime mortars.

It is mapped as Criterion (Partial) under C3. Materials Management – C3.2 & C3.1 (Reduce/Recycle, Narrow/Close) because the paper demonstrates clinker reduction via SCMs and the valorisation of FA as an industrial by-product, but it does not formulate a building-level SBTool indicator such as "% SCM of total cementitious content for the whole building with explicit scoring thresholds"; instead, the metric remains at mortar-mix level within a specific wall functional unit.

Recycled Biogenic Components

In Silva et al.(2023), Recycled Biogenic Components are operationalized through the incorporation of bamboo-waste particles (a by-product of glue-laminated bamboo production) into earth mortars at 0, 3, 6 and 9 vol%, with corresponding mix compositions expressed in kg/m³ of bamboo particles per m³ of mortar and then per m² of plastered wall in the LCA. The implicit KPI is therefore the share of recycled biogenic aggregate in the plaster mix (vol% and/or kg of bamboo waste per m³ of mortar, linked to associated GHG reductions). This maps to C. Resource Management – C3. Materials Management – C3.2 (Recycle, Close) because it demonstrates closed-loop use of a bio-waste as secondary raw material, but it is classified as Criterion (Partial) since even if the concept (recycled content) is the same, the denominator, unit and boundary are not plug-and-play with SBTool's KPI.

Reclaimed Components Substitution Rate

In Tomczak et al. (2023), the Reclaimed Components Substitution Rate is effectively measured as the share of demand elements in the reference design that are replaced by reclaimed components, reported as the "Substitutions (%)" column in the case-study results (number of reused elements divided by total demand elements).
Thus, the KPI is a dimensionless percentage (%) of substituted structural elements at system level, used alongside GWP reduction to evaluate optimisation scenarios. It is mapped to SBTool as Criterion (Partial) under C. Resource Management → C3. Materials Management → C3.4 Design for Deconstruction because SBTool expects a building-level "% reclaimed components by mass/cost", whereas the paper reports element-count shares for a specific structural subsystem and without a standard SBTool boundary or normalisation.

Material Composition Indicators (MCIs)

In Regine Ortlepp, Karin Gruhler, et al (2016), Material Composition Indicators (MCIs) are defined as bottom-up, stock-based metrics that express the weight of each material type per unit of floor area for typical non-domestic building types (t/m² or kg/m²). The authors derive MCIs by: (i) analyzing an object database of 252 non-domestic buildings from the BKI cost database, (ii) calculating material quantities for structural variants of each building element using densities, (iii) aggregating these into "synthetic" building elements by frequency of occurrence, and (iv) normalizing the total material mass of each element by the building's floor space to obtain MCIs, which are then summed to give a total material indicator per building type.

MCI is mapped as C. Resource Management – C3. Materials Management – Reduce/Narrow, Criterion (Partial) because SBTool conceptually addresses efficient material use and composition but does not yet formalize this specific kg/m² composition profile with explicit thresholds or scoring rules. The construct matches the SBTool criterion intent, while the exact KPI and scoring remain only partially aligned—hence "Criterion (Partial)" rather than a full Criterion-Exact match.

Recovery Score (R-score)
In Atta et al. (2021), the Recovery Score (R-score) is introduced as a synthetic indicator of the overall material recovery potential of a building. It combines four dimensionless ratios: the share of recyclable components (Rc), reusable components (Ru), non-toxic materials (Nx) and uncoated elements (Ns) in the total building mass. The score is calculated as: R-score = (Rc + Ru + Nx + Ns) / 4,
and therefore, ranges from 0 to 1, where higher values indicate greater potential for material recovery at end-of-life. In the case study, these ratios are obtained directly from the BIM model by tagging each element according to its recyclability, reusability, toxicity and surface treatment, and then computing their mass fractions; the KPI is thus a dimensionless score (0–1), often reported as a percentage (%) at the whole-building level. From an SBTool perspective, this indicator is mapped as Criterion–Partial under C. Resource Management → C3. Materials Management → C3.4 Design for deconstruction: SBTool already considers recycled and reusable material shares and deconstruction-friendly design, but it does not define an explicit aggregated "recovery score" that simultaneously integrates recyclability, reusability, non-toxicity and absence of coatings into a single KPI. R-score therefore refines and quantifies a subset of existing SBTool concerns rather than introducing a completely new criterion, which justifies its classification as Criterion (Partial).

Material Footprint (MF)
In Mostert et al., Material Footprint (MF) is operationalized at product/building level using a footprint-based LCA of recycled concrete. MF is defined via Raw Material Input (RMI) the mass of primary raw materials used—and Total Material Requirement (TMR), which adds unused extraction such as overburden and tailings. An openLCA model with GaBi databases covers material production and concrete manufacturing (A1–A3) and demolition/recycling stages (C1–C3). For each process, the masses of primary materials (cement, aggregates, fuels, etc.) are converted into RMI/TMR and expressed per functional unit: 1 t of recycled aggregate, 1 m³ of concrete, or 1 m² of gross floor area (GFA) of the structure. Thus, MF is reported as kg or tons of raw materials per functional unit, providing a building-scale resource footprint. Within SBTool this indicator is conceptually aligned with C. Resource Management – C3. Materials Management, since it explicitly measures the overall demand for primary raw materials associated with the building's material choices. However, SBTool does not currently define a dedicated "material footprint" criterion or an RMI/TMR-based

KPI; instead, C3 is operationalized through more fragmented indicators such as recycled content, recyclability and design-for-deconstruction. For this reason, MF is classified as a Criterion-Partial indicator: it quantifies the same resource-efficiency construct targeted by C3, using a compatible LCA method and functional units, but in a more aggregated form than any single existing SBTool criterion.

Substitution Potential for Materials (SPM)

The indicator is implicit in the Zero Waste Index (ZWI) framework applied by Sujai & Juwana (2021) for Hotel XYZ in Bandung.

In their study, they quantify, for each waste management option (mainly recycling and composting), the "potential total virgin material substituted (kg)" as part of the ZWI resource substitution outputs. (SPM) quantifies, in kg of virgin material saved, the effect of recycling schemes on primary resource demand. It aligns with SBTool's C3 Materials Management criteria but introduces a more explicit, ZWI-based measure of virgin material substitution, which is why it is mapped as a Criterion-Partial indicator supporting Recycle/Reuse in the Close loop.

Reuse Rate for Components (RR)

This indicator can be proposed as a robust quantitative KPI for SBTool's C3.4 "Design for Deconstruction" because it directly measures the intended performance outcome of the criterion: the effective recovery of components for further use. In Küpfer et al. (2021), RR is defined as the mass fraction of structural steel that is re-employed as whole elements in the new structure, expressed as a percentage of total steel mass. This definition is fully consistent with life cycle thinking in EN 15978 and with the emphasis on reuse potential in ISO 20887, where the quantity of components prepared for reuse is a central parameter for assessing circularity at end of life. Unlike the current SBTool scoring, which relies on qualitative checks of design features (e.g. reversibility of joints, accessibility of elements), RR is an outcome-based, physically measurable indicator that can be calculated both ex ante (from the design model and bill of quantities) and ex post (from deconstruction and reconstruction inventories). It increases monotonically as circular performance improves (a higher RR always means more reuse and less new production), is comparable across projects once normalized by total mass, and reduces subjectivity by replacing descriptive scores with a transparent mass-balance. For these reasons, RR is an appropriate Criterion-Partial enhancement of C3.4 and a strong candidate to evolve SBTool's qualitative DfD evaluation into a quantifiable, reuse-oriented KPI.

Construction Complexity

The "Construction Complexity" indicator is introduced by Küpfer et al. (2021) as one of the four performance criteria in their multi-criteria decision framework for designing steel structures with reused components. It quantifies how difficult the structure is to fabricate and assemble when integrating reclaimed elements, using as KPI the number of colinear joints in the top and bottom chords of the truss. In practice, the authors count how many joints occur along continuous chord lines where several members meet in line, since a higher number of such joints implies more cutting, welding, bolting, alignment operations, and site coordination. The indicator is therefore expressed in a dimensionless unit as a simple count (number of joints), with lower values indicating lower construction complexity and thus more efficient, less labour-intensive assembly. Within SBTool, this indicator is mapped to C. Resource Management → C3. Materials Management → C3.4 Design for Deconstruction and classified as a Criterion-Partial indicator: it captures how design choices for reuse affect the practicality of assembly and future reuse/refurbishment (more joints often mean more complicated disassembly).

New Product to Wood Residue Ratio (MDF)
The New Product to Wood Residue Ratio (MDF) expresses the percentage of MDF residues that are recovered during selective disassembly and reintroduced into recycling flows. In Melella et al. (2021), the material inventory and C3 waste processing data allow its calculation as a mass-based ratio between recycled MDF fractions and total MDF residues. The KPI is therefore defined as a percentage (%). The indicator aligns with SBTool's C3 Materials Management criteria but extends them by quantifying end-of-life recycling efficiency, making it a Criterion-Partial indicator that supports the "Recycle" strategy within the Close loop.

Reusability Index (RI)
The Reusability Index (RI), used in the selective low CO_2eq disassembly and demolition study by Melella, Di Ruocco, and Sorvillo (2021), expresses how much of a building's component stock can be dismantled and reused rather than downcycled or landfilled. Based on the pre-demolition inventories for the Avenida Central Building and the Melopee school, the authors classify each technical element (beams, slabs, cladding, etc.) according to its condition, connection type, and market prospects, and then derive an index representing the share of components that can be recovered for direct reuse. In practical terms, the KPI can be expressed as the percentage of total component mass (%) (or, alternatively, a dimensionless 0–1 score) that is technically and economically reusable according to the audit results.
Within SBTool, RI is conceptually aligned with C3. Materials Management → C3.4 Design for deconstruction, which aims to maximise the share of components that can be recovered intact at end-of-life. SBTool currently treats C3.4 via qualitative scoring rules (e.g. presence of reversible connections, documentation, etc.) rather than a quantitative reuse rate. RI therefore becomes a Criterion-Partial indicator under C3.4: it captures exactly the performance outcome that SBTool seeks (reusable vs non-

reusable material stock), but extends the existing framework by providing an explicit, mass-based KPI that could be applied to building-scale pre-demolition audits.

Rate of Reusable vs Recyclable Steel

This indicator, introduced by Küpfer et al. (2021), measures the proportion of steel elements that can be directly reused versus those that must be recycled after deconstruction. In their study on reusable steel trusses, the authors define a reuse rate (RR) as the ratio of the mass of steel elements recovered intact for direct reassembly to the total steel mass, with the remaining fraction treated as recyclable scrap. The KPI is therefore expressed in percentage of total steel mass (%), distinguishing the mass fraction reused (%) from the mass fraction recycled (%) for each structural alternative.
Within SBTool, this indicator is conceptually aligned with C3.4 – Design for Deconstruction, which aims to enhance material recovery and reusability at end of life. However, SBTool currently operationalises C3.4 through qualitative scoring rules rather than through a quantitative mass-based metric. Consequently, the "Rate of Reusable vs Recyclable Steel" is classified as a Criterion-Partial indicator under C3. Materials Management: it directly quantifies the performance outcome that C3.4 seeks to promote but extends beyond SBTool's present framework by providing an explicit, percentage-based KPI.

LCC for Formwork Materials

In Tighnavard et al. (2024), a life-cycle cost (LCC) indicator is used to compare four reusable formwork systems (plastic, steel, plywood and timber) from cradle to cradle over 1 and 50 use cycles. The economic assessment includes production cost of materials (PC), labour cost for assembly and use (LC), transport cost (TC), and end-of-life resale income (EOF) for materials such as steel, plastic and wood. Conceptually, this LCC for formwork materials is aligned with SBTool's F1.1 global cost criterion, as it applies a discounted life-cycle cost approach—PC + LC + TC minus residual value—to support comparison between design alternatives. However, it is limited to a single temporary component (wall formwork) and to a specific functional unit (a 10.8 m² wall, assessed for 1 or 50 reuse cycles), whereas F1.1 aggregates the costs of the entire building and expresses them in €/m²·year. For this reason, it is mapped as a Criterion-Partial indicator under F1 – Life-Cycle Cost. The LCC is expressed in monetary terms and reported in U.S. dollars for both one-cycle and fifty-cycle scenarios; accordingly, the KPI is defined as the discounted total cost (PC + LC + TC – EOF) per functional unit of formwork, expressed in USD.

Recycling Route Cost Comparison (DEc4)

is an economic indicator developed to compare the total cost per tonne of gypsum waste managed via recycling versus landfilling. It aggregates, for each route, the rental of skips, loading and unloading operations, gate fees and taxes, and transport costs. The KPI is defined as the difference between the recycling route cost and the

landfilling route cost, both expressed in €/t (DEc4.1 – DEc4.2), where negative values indicate that recycling is cheaper than disposal (Jiménez-Rivero & García-Navarro. 2016).
From the perspective of SBTool, DEc4 is conceptually aligned with F1. Life-Cycle Cost, which also uses monetary indicators to compare alternative scenarios over the life cycle. However, while SBTool's F1.1 criterion aggregates all costs of the building into a global cost expressed in €/m²·year, DEc4 is limited to the end-of-life management of a single material (gypsum) and is expressed in €/t. For this reason, DEc4 is classified as a Criterion-Partial indicator under F1: it uses the same economic decision logic and type of KPI (cost per functional unit for comparing options) but covers only a subset of the life-cycle cost domain addressed by SBTool.

Energy Footprint (EF)
Is defined in the reviewed study as the total life-cycle demand for non-renewable primary energy, calculated with the Cumulative Energy Demand method (CED, non-renewable) and expressed as MJ per functional unit (e.g. per ton of recycled aggregate concrete, per m³ of concrete, or per m² of gross floor area of the structure). The LCA model includes extraction, processing of aggregates, transport, concrete production and end-of-life management, and EF is reported as a single aggregated indicator for each scenario. From a circular-economy perspective, EF captures a Reduce/Narrow mechanism: it quantifies how design and recycling strategies reduce non-renewable energy use per unit of structural performance. (Müller, Bauer, Schmidt. 2022).
Within SBTool, EF is most closely related to the A2. Energy Efficiency category, particularly A2.2 Embodied non-renewable primary energy, which also uses non-renewable primary energy (MJ or kWh per m²) as its main metric. However, SBTool does not define a unified "energy footprint" criterion that aggregates all non-renewable energy inputs across the full life cycle and across multiple functional units; instead, A2 is disaggregated into separate criteria for embodied energy (A2.2), final energy and specific heating/cooling needs (A2.3, A2.6, A2.7). Consequently, EF is conceptually aligned with the A2 Energy Efficiency issue, uses a compatible physical quantity (non-renewable primary energy), but does not correspond one-to-one to any single SBTool criterion or KPI. For this reason it is justified to classify EF as a category/issue-partial indicator: its underlying construct is already partially represented in SBTool through A2.2 and related criteria, yet the specific "energy footprint" formulation used in the paper (life-cycle CED non-renewable, MJ/FU) is not explicitly operationalised in the current SBTool framework and would require adaptation to be fully integrated.

For all Criterion-Partial indicators, the proposed KPIs deliberately avoid introducing new ad hoc metrics. Instead, each indicator is anchored to one or more existing SBTool

KPIs, either as a disaggregated sub-scope, a scenario-based delta, or a composite index built from current data structures. This strategy is consistent with EN 15978 and the EU Level(s) framework, which explicitly allow LCA and LCC results to be reported by life-cycle stage, component, or scenario, and with ISO 20887, which treats reusability and ease of deconstruction as parameters of design for disassembly rather than as separate domains. As a result, the proposed KPIs are methodologically compatible with SBTool and can be defended as valid refinements that enhance circular economy visibility for university campuses without disrupting the underlying assessment logic. Therefore, these indicators are also excluded from the key gap identification procedure, as they do not represent genuinely missing constructs in SBTool but rather strengthen and fine-tune criteria that are already conceptually present within the existing framework.

4.2.5 Category (Partial) Indicators evaluation:

Table 19. Category-Partial Indicators

Category (Partial) Indicators	SBTool slot (Issue →Category→ Criterion)	10R (primary)	Loop
1. Durability & Replacement Cycles	E. Service Quality E2. Optimization and Maintenance	Repair/Refurbish	Slow
2. Fossil Resource Scarcity	A. Energy A2. Energy Efficiency/A3. Renewable Energy	Reduce	Narrow
3. Effectiveness of Pre-Deconstruction Audit	C. Resource Management C3. SBTool Materials Management C3.4 Design for deconstruction	Reuse/Recycle	Close
4. Product market price (€/tonne)	F. Economy	not CE-mechanism specific	

According to the SBTool mapping results, four of the extracted indicators are partially mentioned at the Issue level in SBTool. Therefore, each indicator is evaluated in this section by analysing its source paper, in order to understand it better and to assess its potential to be selected as a gap in SBTool. The fourth indicator in this list, Product market price (€/tonne), is excluded from the evaluation because it is not CE-specific and therefore contradicts the aim of this study.

Durability & replacement cycles:
In Paiva et al. (2022), "durability & replacement cycles" are not measured through dedicated physical durability tests but are incorporated into the LCA model via module B4 (Replacement) as the number of plaster replacements over a 50-year reference period. The functional unit is a wall with a 50-year service life, and durability is explored through sensitivity scenarios with one, two and three replacements of earth-based mortars (EMB), compared to a single replacement for conventional mortars. The practical KPI is therefore the count of replacements in 50 years (–), which drives the additional production, transport and end-of-life flows and, consequently, the total climate change impact in kg CO_2-eq/m² over 50 years. The authors explicitly note that durability and service-life data should be refined in future work, which confirms that the indicator is treated as a scenario parameter rather than a fully calibrated, standalone durability metric.

Fossil Resource Scarcity:
FRS in Tighnavard et al. (2024), is calculated by ReCiPe from all fossil-based energy and material flows in the life cycle:
fossil fuels used in material production (plastic, steel, etc.),
fuels for transport and construction,
credits/debits from recycling and energy recovery at end of life.
The functional unit in the paper is 1 m² of formwork for a concrete wall, over the defined life-cycle scenario (1 use or 50 uses), where FRS – LCIA midpoint indicator from ReCiPe midpoint (H), expressed as kg oil-eq per m² of formwork over the life cycle (1 or 50 uses).

Effectiveness of Pre-Deconstruction Audit:
The "Effectiveness of Pre-Deconstruction Audit" indicator (DT1) is measured in the reviewed paper as a composite of three sub-KPIs (existence of audit, deviation in total gypsum waste, and deviation in recyclable gypsum waste). This reflects the central role of pre-deconstruction audits in ISO 20887 and EN 15978, which emphasize material inventory accuracy as a prerequisite for effective selective dismantling and circular recovery pathways. The use of percentage deviation between predicted and actual waste quantities is methodologically robust, since it is based on direct measurement of mass flows over a standardized functional unit. Thresholds used in the paper:
Audit exists = required / DT1.2 < 10% = good accuracy / DT1.3 < 20% = acceptable accuracy for recyclable waste
If all three conditions are satisfied → Audit considered effective (Jiménez-Rivero et al. 2016).

4.2.6 Issue (Partial) Indicators evaluation:

Table 20. Issue-Partial Indicators

Issue (Partial) Indicator	SBTool slot (Issue →Category→ Criterion)	10R (primary)	Loop
1. Acidification Potential (AP)	A. Energy / C. Resource Management	Reduce	Narrow
2. Environmental Score (E-score)	A. Energy / C. Resource Management	Reduce	Narrow
3. Abiotic Resource Depletion Potential (ADP-elements)	A. Energy +C. Resource Management	Reduce	Narrow
4. Environmental Point Score (ReCiPe)	A. Energy / C. Resource Management	Reduce	Narrow

Acidification Potential (AP)

In Schützenhofer et al. (2022), AP is treated as a standard LCA impact category alongside GWP and PENRT. They follow the EI3 / OI3-based LCA (IBO guidelines) using Baubook eco2soft factors and applied this methodology to all main building components (outer wall, inner wall, roof, ground floor, upper floor, terrace). Conceptually, AP expresses the potential contribution of emissions (SO_2, NOx, NH_3, etc.) to acidification of soil and water, aggregated and converted to equivalent kg of SO_2 – this is standard LCIA practice and is exactly how the EI3/OI3 indicators define AP. AP is a cross-cutting environmental pressure indicator that depends simultaneously on energy use and material/waste management. SBTool partly covers its underlying causes through several energy and resource criteria, but it does not adopt AP or kg SO_2-eq as an assessment metric. For this reason, AP is classified as Area (Partial), spanning A. Energy and C. Resource Management rather than matching a single SBTool criterion.

Environmental Score (E-score)

Environmental Score (E-score) is an LCA-based composite indicator that quantifies the environmental performance of building materials through a normalized single-score methodology. In the examined paper, the indicator is computed using the IMPACT2002+ method, which aggregates climate change, resources, human health and ecosystem-quality impacts into a unified damage score expressed in Pers/yr.

These results are normalized within each material category to obtain Ei, ensuring comparability across alternatives, and are then weighted by a secondary-life factor w that reflects the proportion of reusable components. The final environmental score is calculated as a mass-weighted average of the normalized impacts multiplied by the reuse factor, yielding a dimensionless KPI ranging from 0 to 1 (Islam Atta, Emad Bakhoum, Mohamed Marzouk. 2021).
Within SBTool, this indicator does not correspond to any single criterion or predefined KPI. While its components relate to several environmental issues—particularly climate change (A1), energy efficiency (A2), and materials management (C3)—SBTool does not integrate LCA-based single-score assessment nor reusability-weighted environmental performance. For this reason, the indicator is classified as Area-Partial, meaning that it aligns conceptually with the environmental assessment area of SBTool, but no direct criterion or KPI exists that captures its scope or methodological structure.

Abiotic Resource Depletion Potential (ADP-elements)
In paper Pilar Mercader-Moyano et al. (2020), ADP-elements is calculated as part of the life cycle assessment using the CML baseline method implemented in SimaPro. The authors model the full life cycle of the studied building solution (insulation system) and then obtain ADP-elements directly from SimaPro as a midpoint impact category. The KPI of it is: Abiotic Resource Depletion (elements): kg Sb-eq per functional unit, where the functional unit is 1 m² of the insulation system over the defined life-cycle scenario. Since ADP-elements depend simultaneously on energy-related processes and material/waste flows, but have no dedicated, unit-aligned KPI in SBTool, it cannot be matched to a single Issue.

Environmental Point Score (ReCiPe)
In Küpfer et al. (2021), Environmental Point Score (ReCiPe) is used as a single environmental performance indicator to compare all design alternatives for the steel truss with different reuse rates. It is calculated using the ReCiPe Endpoint (H) v1.12 impact method, which aggregates a wide range of environmental damage categories (climate change, human health, ecosystem quality, fossil resource depletion, etc.) into a single score in "ReCiPe points". This indicator is conceptually consistent with SBTool's environmental areas—primarily A. Energy (A1 GHG emissions, A2 energy efficiency) and C. Resource Management but it does not correspond to any single SBTool criterion or KPI, because SBTool uses disaggregated mid-point metrics (e.g. kg CO_2-eq/m², MJ non-renewable primary energy) rather than a unified ReCiPe endpoint score. For this reason, the Environmental Point Score is classified as an issue/area-partial indicator: it captures the combined effect of several SBTool environmental issues but is not explicitly operationalized as a stand-alone criterion in the current SBTool framework.

4.2.7 Conclusion of the cross mapping:

The cross-mapping exercise and subsequent grouping of indicators according to their level of presence in SBTool (Criterion–Exact, Criterion–Partial, Category–Partial and Issue–Partial) provided a first structured picture of how circular-economy-related constructs are currently addressed by the protocol. Out of the 51 unique indicators extracted from the literature, 11 were classified as Criterion–Exact, meaning that their issues, criteria and KPIs are already fully operationalized within SBTool; these indicators were therefore excluded from the subsequent gap-identification stage, as they do not represent missing constructs but rather areas where SBTool is already complete. A further 30 indicators were classified as Criterion–Partial; in all cases they are anchored to one or more existing SBTool criteria and represent either a disaggregated sub-scope, a scenario-based delta or a composite index built from current data structures. As such, they refine and enhance criteria that are already conceptually present and were likewise excluded from gap identification. The remaining 8 indicators, distributed across the Category–Partial and Issue–Partial groups, were carried forward to the next step. In a further refinement step, one of the Category–Partial indicators was excluded because it is not genuinely circular-economy-related, leaving 7 indicators to be evaluated in greater detail to identify those that reveal a substantive SBTool gap and hold potential to strengthen the tool in the context of university campuses and the DRH case study.

4.3 Results of the Gap-Identification Process

This section reports the empirical results obtained by applying the methodology outlined in Section 3.9 It first summarizes the outcomes of the Delphi validation and AHP weighting of criteria, then presents the stepwise shortlisting of indicators, the detailed comparative assessment of the two shortlisted candidates and, finally, the identification of the key SBTool gap indicator.

4.3.1 Delphi validation results

Round 1: initial critique of criteria

In the first Delphi round, experts were presented with a set of evaluation criteria derived from the academic literature, including Impact on Circularity, Evidence Strength, Measurability & Data Availability, Ease of SBTool Integration and Policy/Market Alignment. For each criterion, they were asked to rate on a 1–5 Likert scale (1 = "not at all", 5 = "very much"):

- its relevance for prioritising SBTool gaps in the context of university campuses; and
- the clarity of its definition.

An open-ended question at the end of the survey invited general comments, critiques and suggestions for additional or alternative criteria. Descriptive statistics (average ratings and response distributions) were generated and inspected to identify criteria that were consistently rated as relevant but whose definitions were perceived as ambiguous or incomplete.

Overall, all initial criteria reached relatively high relevance scores (around 4/5 on average), indicating broad agreement that they capture important aspects for prioritising SBTool gaps. However, qualitative comments highlighted two main needs: (i) to broaden the notion of integration so that it includes not only technical ease of incorporation but also the essentiality of an indicator for the overall SBTool circular-economy framework; and (ii) to explicitly account for how acceptable a potential gap indicator would be for key stakeholder groups on university campuses.

Refinement of the criteria set

On the basis of Round-1 feedback, several modifications were made before launching Round 2. The criterion Ease of SBTool Integration was reframed as Integration Feasibility & Essentiality to capture not only ease of incorporation but also the extent to which an indicator is indispensable for representing a specific circular-economy construct. Impact on Circularity was reformulated as Circularity Impact with a sharpened definition explicitly linked to slowing, narrowing and closing loops. Policy/Market Alignment was expanded to Policy/Market & Territorial Alignment to reflect the multi-scalar regulatory and market context of Italian university campuses.

Finally, a new criterion, Stakeholder Acceptance, was added in response to repeated expert suggestions that the perceived legitimacy and usability of a new indicator by campus actors is critical for its eventual adoption and should be treated as a separate evaluation dimension rather than being assumed implicitly.

Round 2: re-assessment of refined criteria

Round 2 presented the refined set of six criteria—Circularity Impact, Evidence Strength, Measurability & Data Availability, Integration Feasibility & Essentiality, Policy/Market & Territorial Alignment and Stakeholder Acceptance—together with updated definitions that incorporated the experts' earlier comments. Experts were again asked, for each criterion, to rate its relevance for prioritising SBTool gaps and the clarity of its definition on the same 1–5 Likert scales.

As shown in the Typeform summary charts (average ratings between approximately 3.8 and 5.0 for relevance and between 3.2 and 4.8 for clarity), all six criteria were confirmed as both relevant and sufficiently clear. Measurability & Data Availability, Circularity Impact and Stakeholder Acceptance received particularly strong support as key drivers for gap prioritisation, signalling that feasibility in real campus contexts and direct influence on loop performance are central concerns for experts.

Use of Delphi outputs in the thesis

The Delphi procedure thus served two functions. First, it validated and stabilised the evaluation criteria, ensuring that they reflected expert consensus rather than only the researcher's perspective. Second, it led to the explicit introduction of Stakeholder Acceptance and to refined formulations of the other five criteria, which were subsequently used in both the qualitative indicator assessments and the AHP weighting exercise. The final, Delphi-validated criteria set constitutes the backbone of the indicator evaluation framework presented in Section 3.9 and applied in the stepwise gap-identification process reported below.

4.3.2 AHP weighting results

Following this procedure, all 15 unique pairs of criteria were compared with respect to their importance for identifying the key SBTool gap indicator. In practical terms, Measurability & Data Availability was judged slightly to moderately more important than Stakeholder Acceptance and Policy/Market & Territorial Alignment, and clearly more important than Integration Feasibility & Essentiality and Evidence Strength. Stakeholder Acceptance and Policy/Market & Territorial Alignment were considered equally important, and both slightly more important than Circularity Impact. Circularity Impact was given higher importance than Integration Feasibility & Essentiality and Evidence Strength, reflecting its direct link to circular-economy performance.

The completed comparison matrix was processed by AHP-OS, which calculates the principal right eigenvector of the matrix to obtain a normalised weight for each criterion and automatically checks internal consistency. The resulting priorities are reported in Table 21.

Table 21. Criterion comparison matrix.

Criterion	Weight
Measurability & Data Availability	0.214
Stakeholder Acceptance	0.199
Policy/Market & Territorial Alignment	0.199
Circularity Impact	0.180
Integration Feasibility & Essentiality	0.114
Evidence Strength	0.094

The software also returned a Consistency Ratio (CR) of 0.012 (1.2%), indicating that the judgements are highly consistent and well below the commonly accepted 10% threshold in the AHP literature (Saaty, 2008). These weights were then used in the final stage of indicator evaluation: for each candidate gap indicator, its performance on the six criteria was scored and combined using the AHP-derived weights. This ensured that the comparison of indicators was not driven by arbitrary or implicit preferences, but by a transparent and reproducible weighting scheme grounded in an established decision-making method.

4.3.3 Stepwise Shortlisting of Candidate Gap Indicators

1. Initial pool of candidate indicators

Following the exclusion of Criterion–Exact and Criterion–Partial indicators described in Section 4.2, the gap-identification process continued with a reduced pool of seven indicators that are only partially represented in SBTool at category or issue level and whose underlying constructs are explicitly related to circular economy. Three of these are Category–Partial indicators, meaning that their thematic content appears in SBTool only at category level, while no dedicated issue or criterion exists. Four are Issue–Partial indicators, whose constructs are present as impact categories or environmental scores but without a fully operational circularity-oriented formulation.

2. Exclusion of Issue-Partial LCA indicators

The first screening step examined the four Issue–Partial indicators:

- Acidification Potential (AP)
- Environmental Score (E-score)
- Abiotic Resource Depletion Potential (ADP-elements)
- Environmental Point Score (ReCiPe)

All four originate from classical life cycle impact assessment (LCIA) practice and are already widely used as part of multi-impact environmental evaluations. In SBTool, environmental performance is already addressed through energy and resource-related criteria that assume a multi-impact LCA background, even if specific impact categories are not always enumerated. The four indicators above would therefore primarily extend the impact coverage rather than introduce a new circularity mechanism or a missing category/issue node.

AP and ADP-elements represent additional impact categories (acidification and abiotic resource depletion), while E-score and ReCiPe point score are composite indices aggregating several environmental impacts into a single number. None of them directly target CE levers such as adaptability, reuse, reversibility or design for deconstruction, nor do they change the underlying assessment paradigm of SBTool; they remain generic environmental impact metrics.

For this reason, and in line with the definition of a SBTool gap adopted in Section 3.9, these four Issue–Partial indicators were excluded from further consideration. They refine environmental impact analysis but do not qualify as structural CE gaps at category/issue level.

3. Conceptual screening of Category-Partial indicators

The second screening step focused on the three Category–Partial indicators:

1. Durability & Replacement Cycles
2. Fossil Resource Scarcity
3. Effectiveness of Pre-Deconstruction Audit

All three are only partially represented in SBTool at category level but differ in the extent to which they embody genuinely circular-economy constructs aligned with the thesis aims.

- Fossil Resource Scarcity is conceptually related to long-term depletion of fossil energy resources and the transition to renewables. Although resource scarcity is an important sustainability concern, in SBTool this aspect is already addressed indirectly through energy efficiency and renewable energy criteria (A2 and A3) and through broader resource-use indicators. Moreover, the indicator does not operate through CE mechanisms of slowing, narrowing or closing material loops at building level; instead, it reflects the upstream scarcity of a particular energy source. Under the stricter definition of a SBTool gap used in this thesis—centred on missing CE categories/issues—Fossil Resource Scarcity was therefore judged not to represent a distinct circular-economy gap and was excluded from the shortlist.
- Durability & Replacement Cycles, by contrast, directly concerns the service life and replacement frequency of building components, which are critical issues for long-lived, intensively used campus buildings. SBTool's E2 "Optimisation and maintenance" category touches maintenance aspects but does not provide a clear, quantitative KPI for durability and replacement cycles that would explicitly operationalise the "slow loop" logic of circular economy. This indicator therefore remains a strong candidate gap.
- Effectiveness of Pre-Deconstruction Audit focuses on the quality and usefulness of audits carried out before deconstruction to enable selective dismantling and maximise recovery of components and materials. It is strongly tied to SBTool's C3.4

"Design for deconstruction" but is not explicitly operationalised through a dedicated indicator or scoring rule. As such, it offers clear potential to strengthen SBTool's representation of reuse/recycle "close loop" strategies at end-of-life and is retained as a candidate gap.

4. Resulting shortlist for detailed evaluation

After these two screening stages, the pool of potential SBTool gap indicators was reduced from seven to two Category–Partial indicators:

1. Durability & Replacement Cycles (E. Service Quality – E2 Optimisation and Maintenance; Repair/Refurbish – Slow loop)
2. Effectiveness of Pre-Deconstruction Audit (C3.4 Design for Deconstruction; Reuse/Recycle – Close loop)

Both indicators address CE constructs that are currently only weakly represented in SBTool at category/issue level, are relevant for university campuses and align with the thesis aims of slowing resource flows and improving recoverability in long-lived assets. These two indicators form the shortlist that is examined in depth using the six evaluation criteria and the Delphi–AHP-based weighting scheme presented in Section 3.9. The detailed qualitative assessments and quantitative comparison of these shortlisted indicators are reported in Sections 4.3.4 and 4.3.5.

4.3.4 Detailed Assessment of Remaining Indicators (with Delphi & AHP Integration)

Building on the evaluation framework and the Delphi–AHP weighting procedure described in Section 3.9, this subsection presents a detailed, criterion-by-criterion assessment of the two shortlisted indicators—Durability & Replacement Cycles and Effectiveness of Pre-Deconstruction Audit. The objective is to make explicit how each indicator performs on the six evaluation criteria and how the corresponding 1–5 scores are derived, so that the subsequent quantitative comparison is transparent and replicable.

Previous subsections apply the scoring scale defined in Section 3.9 to the two indicators, discussing required data sources, expected availability in university campuses, alignment with policy and practice, circularity mechanisms, ease of integration into SBTool/ITACA and strength of the supporting evidence. These narrative assessments provide the justification for the scores later used in the AHP-weighted comparison and the final selection of the key SBTool gap indicator.

1. Assessment of Indicator 1 – Durability & Replacement Cycles

Indicator definition and data sources

The Durability & Replacement Cycles indicator is adapted from the life-cycle assessment approach proposed by Paiva et al. (2022), who compute the greenhouse-gas emissions of different earth-based mortars over a 50-year reference period as a function of (i) the impact per unit of material, (ii) the exposed area and thickness of the mortar layer, and (iii) the number of replacement cycles during the building service life. In their formulation, the total impact of a finishing system is obtained by multiplying the unit impact by the area and by the number of times the system is produced and replaced within the reference period, where the number of replacements is derived from the ratio between reference study period and assumed service life of the material.

Transposed to the SBTool/ITACA context, the same logic is used to define a durability-based circularity indicator at building level. For each relevant component of the building envelope (e.g. external cladding, internal finishes, roofing layers), the following data are required:

- the type of material or system applied (e.g. ETICS, ventilated façade, mortar type).

- the area or quantity of each component (m² of envelope, m² of roof, etc.); and
- the assumed service life of each component, expressed in years, relative to a campus-relevant reference period.

In practice, material types and component areas can be obtained from architectural and technical drawings, BIM models and Legge 10/energy reports, while service-life values are taken from ISO 15686-based tables and national guidance, supplemented where possible by campus maintenance records. The indicator thus links the theoretical service life of envelope systems to their contribution to circular performance and life-cycle impacts.

Measurability & Data Availability – score 4/5

When evaluated against the scoring scale defined in Section 3.9, Durability & Replacement Cycles is judged to have high, but not perfect, measurability in a university-campus context. According to the measurement method adapted from Paiva et al. (2022), the indicator requires three main input groups:

1. Material/system type for each envelope component.

For DRH and comparable campus buildings, this information is systematically documented in design specifications, construction drawings, BIM models and Legge 10 reports. These sources distinguish, for example, between different façade systems, roofing build-ups and internal finishes, and therefore provide good coverage of the material dimension.

2. Area or quantity of each component

Component areas can be extracted directly from BIM models, quantity take-offs or as-built drawings used for cost estimation and energy modelling. Universities that manage their estates with CAD/BIM-based documentation, as in the case of PoliTo, can obtain these quantities with limited additional processing.

3. Service life (or replacement interval) for each component

This is the most challenging input. Campus asset registers and facility-management systems rarely store explicit service-life values for each envelope system; instead, they may contain partial information on past interventions. To calculate the indicator, service-life values therefore need to be taken from external reference sources such as the ISO 15686 series and national durability catalogues and adapted through expert judgement to the local exposure and maintenance conditions. Historical maintenance data, where available, can be used to calibrate or check these assumptions, but they are not yet complete for all components.

Because material types and component areas are well documented and can be retrieved from existing project documentation, while service-life values require a combination of reference tables and expert assumptions rather than fully recorded campus data, the indicator is rated 4/5 for Measurability & Data Availability: it can be calculated with mostly standard data plus some additional estimation work, but it does not reach the highest score because one of its input groups (service life) is not yet routinely stored in university information systems.

Stakeholder Acceptance – score 4/5

For the Durability & Replacement Cycles indicator, stakeholder acceptance is evaluated with respect to the main actors involved in campus building management: technical offices, facility managers, maintenance contractors, designers and, indirectly, financial and planning units.

From a conceptual point of view, durability and replacement frequency are familiar ideas for these groups. Service-life prediction and maintenance planning are already recognised as core tasks for building owners and managers, who need to forecast performance, failures and maintenance costs over time (de Brito & Silva, 2020; Marino & Marrone, 2020). In this sense, an indicator that expresses how many times a façade, roof or finish will have to be replaced within a given reference period is close to the language of current practice, rather than introducing an entirely new technical construct.

The measurement method adapted from Paiva et al. (2022) also supports acceptance, because its logic is straightforward to communicate: the total impact of a component over the reference period is a function of its impact per unit, its area and the number of times it is replaced, with the number of replacements derived from the ratio between reference period and service life. This "impact × area × number of replacements" structure can be explained to non-specialists without going into detailed LCA modelling, making it easier for campus actors to see how design choices (for example, selecting a more durable façade system) directly affect both environmental and maintenance outcomes (Paiva et al., 2022).

The broader literature on sustainability indicators emphasises that indicators are only effective if stakeholders see them as meaningful and usable, not merely technically correct. Bell and Morse (2008) stress that stakeholder participation and perceived legitimacy are essential conditions for successful indicator systems. Similarly, de Olde et al. (2017) and Domingues et al. (2018) highlight that indicator selection and use should reflect the concerns and knowledge of the people who will apply them; otherwise, trust in the assessment framework remains limited. Reviews of sustainability and energy indicator sets also use stakeholder engagement and perceived relevance as explicit quality criteria (Gunnarsdóttir et al., 2020).

In the specific case of durability, recent work on life-cycle prediction and maintenance of buildings underlines that stakeholders need to be aware of tools for optimising maintenance and rehabilitation, and that service-life information is a key input for rational decision-making (de Brito & Silva, 2020; Marino & Marrone, 2020). Because the Durability & Replacement Cycles indicator organises information that stakeholders already work with (component types, areas and expected service life) into a single, interpretable measure, it has good potential to be perceived as both credible and useful.

However, two limitations temper this positive assessment. First, detailed service-life modelling is still relatively new in many institutional contexts, and some campus stakeholders may see it as an additional analytical layer beyond their usual budgeting and maintenance routines (de Brito & Silva, 2020). Second, the indicator's explicit framing in terms of circular economy (slow loops and reduced material throughput) may require additional explanation, since most existing durability tools are primarily presented in terms of cost and performance rather than circularity.

For these reasons, Durability & Replacement Cycles is considered highly, but not universally, acceptable to stakeholders and is therefore assigned a score of 4/5 for Stakeholder Acceptance.

Policy/Market & Territorial Alignment – score 4/5

The Durability & Replacement Cycles indicator aligns well with the main international and European policy frameworks that shape sustainable construction and circular economy in the built environment, even if it is not yet mandatory as a stand-alone requirement in the Italian university context.

At the international level, the ISO 15686 series explicitly frame service-life planning as part of sustainable construction and life-cycle management. ISO 15686-1 sets out general principles for service-life planning over the full life cycle of a building, emphasising the link between service-life estimates, maintenance strategies, environmental impacts and whole-life value (ISO, 2011). ISO 15686-5 extends this to life-cycle costing, underlining that economic performance should be evaluated with explicit reference to the service life of components and systems (ISO, 2017). Recent work further connects service-life planning and durability with circular-economy assessments, arguing that extending service life and planning for multiple life cycles of components are central levers for resource efficiency (Bourke & Kyle, 2019).

At the EU policy level, durability and long service life are increasingly recognised as part of the transition to a circular economy. The EU Circular Economy Action Plan explicitly identifies construction and buildings as a priority sector and calls for measures to improve circularity throughout the building life cycle, including longer life expectancy of built assets and improved management of construction and demolition waste (European Commission, 2020a, 2020b). A related study commissioned by the European Parliament on product longevity stresses durability and extended product lifetimes as key policy objectives to reduce resource use and waste, which is conceptually consistent with durability-based indicators for building components (Marcus et al., 2020).

The Level(s) framework, promoted by the European Commission as a common EU framework for sustainable buildings, also embeds life cycle hinking and implicitly supports durability-oriented metrics. Level(s) provides a set of core indicators to track environmental performance of buildings over their entire life cycle and is presented as an entry point for applying circular-economy principles in the built environment (Dodd, 2021; European Commission, 2021). While Level(s) does not define a single "durability" indicator, it requires designers and clients to consider life-cycle performance, resource efficiency and circular strategies, creating a policy environment where indicators related to replacement cycles and service life are increasingly relevant.

In the Italian territorial context, the ITACA protocol is widely adopted by regions as an environmental sustainability assessment tool for buildings, including public and non-residential assets (Iiritano, 2021; Interreg Europe, 2020). ITACA and related regional systems are themselves aligned with European frameworks and use a set of criteria that reflect life-cycle environmental performance, even if durability is not yet singled out as a dedicated circular-economy indicator. This means that a durability-based indicator would be compatible with the direction of Italian assessment practice and could be integrated into national or regional adaptations of SBTool/ITACA without contradicting existing policy signals.

For university campuses specifically, buildings are typically long-lived, subject to multiple refurbishments and managed within public or semi-public investment frameworks. In this setting, an indicator that explicitly links service life and replacement cycles to circular performance fits well with the broader policy push towards circular, resource-efficient and long-lasting building stocks, but it is not yet required by law or by standard campus guidelines. On this basis, the policy/market and territorial alignment is strong, but not fully codified, and Durability & Replacement Cycles is therefore assigned a score of 4/5 for Policy/Market & Territorial Alignment.

Circularity Impact – score 4/5

By extending the service life of components and reducing the number of replacement cycles, this indicator directly activates the "slow" loop of the circular economy (maintain, repair, refurbish). A lower replacement frequency means less material throughput, fewer construction activities and reduced embodied impacts over time, which is repeatedly highlighted in durability and life-cycle assessment studies. The effect is substantial but focused mainly on slowing and narrowing loops rather than closing them through reuse and high-quality recycling, so a score of 4 is assigned.

Integration Feasibility & Essentiality – score 5/5

Within SBTool/ITACA, Durability & Replacement Cycles can be integrated as a quantitative reinforcement of the existing "Service Quality / Optimisation and Maintenance" area, by adding an explicit KPI that links expected service life to reference periods and replacement counts. This does not conflict with energy or material criteria and avoids double counting if clearly located at category/issue level. At the same time, it fills a structural circularity gap: SBTool currently lacks a direct indicator for how design decisions influence the temporal profile of replacements and associated impacts. For this reason, the indicator is rated 5 on Integration Feasibility & Essentiality.

Evidence Strength – score 4/5

The evidence base for using durability and replacement cycles as a sustainability indicator is relatively strong, both conceptually and empirically. At methodological level, the ISO 15686 series provide a recognised framework for service-life planning in buildings and explicitly links design, maintenance and replacement strategies to long-term performance and resource use. This standards family has been widely taken up in research on service life and is frequently used as a reference for developing service-life-based indicators and models (e.g., Silva & de Brito, 2021; Gervasio & Dimova, 2018).

Recent reviews underline that the service life of building envelopes and components is a key driver of environmental and economic outcomes. A critical literature review by Silva and de Brito (2021) synthesises empirical evidence from more than 100 studies and shows that durability and service-life prediction are central for future frameworks that integrate life-cycle assessment (LCA) and life-cycle costing (LCC) in building envelopes. Their work also highlights the need for better integration of service-life data into environmental assessment tools, which directly supports the rationale for a Durability & Replacement Cycles indicator.

Several quantitative studies demonstrate that assumptions on service life and replacement cycles can significantly alter LCA results. Grant and Ries (2013) show that different building service-life models lead to substantial variations in cumulative and annual life-cycle impacts, because maintenance, repair and replacement are treated differently in each model. In a follow-up study, Grant et al. (2014) apply combined service-life prediction and LCA to envelope assemblies and confirm that longer-lasting components can improve environmental performance when maintenance strategies are properly considered. Similarly, Janjua et al. (2021) use a life cycle sustainability assessment framework to explore alternative service-life scenarios for residential buildings and find that changes in service life can materially affect environmental, economic and social indicators over the building life cycle.

Emerging work on long-term comparative assessments reinforces these findings. Costantino et al. (2024), in a Mediterranean climate context, compare heavyweight and lightweight construction systems over extended time horizons and show that assumptions on durability, maintenance and replacement frequency are decisive for both LCA and LCC outcomes. Their conclusions support the idea that indicators explicitly tracking replacement cycles of major elements can provide more realistic pictures of long-term sustainability performance.

The link between durability, replacement cycles and circular-economy objectives is also being explicitly developed. Antonini et al. (2020) argue that durability and reversibility can serve as synthetic indicators of circular potential, because they integrate both service-life extension and the ability to keep materials in higher-value loops. Their work shows that improving durability at the level of main building elements (while considering maintenance and replacement cycles) is consistent with EU circular-economy objectives and with macro-objectives such as "resource-efficient and circular material life cycles." Methodological contributions such as the building LCA model proposed by Gervasio and Dimova (2018) similarly stress that realistic service-life assumptions and replacement profiles are essential inputs when designing robust environmental indicators for buildings.

At the level of concrete measurement methods, studies such as Madrigal et al. (2015) provide operational procedures for estimating the service life of envelope systems using the ISO 15686 factor method, which can be adapted to campus buildings where detailed empirical data are missing. These approaches, combined with service-life datasets and hybrid estimation models for replacement cycles in existing building stocks, further support the feasibility and robustness of indicators grounded in durability and replacement frequencies.

Taken together, these contributions show that:

- service-life planning and durability are recognised components of sustainable building assessment.
- replacement cycles of major building elements have a demonstrable influence on LCA and LCC outcomes; and
- durability is increasingly discussed as a potential circularity indicator, especially when combined with reversibility and design-for-change strategies.

However, the specific formulation adopted in this thesis—linking Durability & Replacement Cycles explicitly to circular-economy loops and to the SBTool category/issue structure for university campuses—has fewer direct precedents in the literature. Most existing studies focus on generic building types, individual envelope systems or national housing stocks rather than on campus buildings and SBTool-type protocols. For this reason, the evidence is judged to be strong but not yet fully consolidated in this particular application domain, and the indicator is therefore assigned a score of 4/5 for Evidence Strength rather than the maximum score.

2. Assessment of Indicator 2 – Effectiveness of Pre-Deconstruction Audit

Indicator definition and data sources

The Effectiveness of Pre-Deconstruction Audit indicator is derived from the set of best-practice indicators developed by Jiménez-Rivero and García-Navarro for end-of-life (EoL) gypsum within the GtoG project. In their framework, indicator DT1 – "Effectiveness of the audit" measures how accurately a pre-demolition audit predicts the quantities of gypsum waste, distinguishing between total gypsum waste and the fraction suitable for closed-loop recycling. In practical terms, DT1 combines: (i) the presence of a pre-demolition audit report for the building; and (ii) the deviation between audited and actually generated gypsum waste, expressed separately for total EoL gypsum and for the recyclable fraction. A small deviation indicates that the audit has correctly identified recoverable resources and has provided a reliable basis for planning selective deconstruction and recycling routes.

In this thesis, the indicator is generalised from gypsum-specific applications to the broader context of campus buildings and SBTool's C3.4 Design for Deconstruction issue. The focus remains on elements typically covered by pre-demolition or pre-renovation audits—such as interior partitions, linings, suspended ceilings, raised floors and other components that can be selectively dismantled and either reused or sent to high-quality recycling. In line with the EU Construction and Demolition Waste Management Protocol and the Guidelines for waste audits before demolition and renovation works, pre-deconstruction audits are understood as structured inspections that document building components, hazardous materials and recovery options before works begin, with the aim of maximising reuse and recycling of construction and demolition waste (CDW).

To operationalise the Effectiveness of Pre-Deconstruction Audit indicator at project level, three groups of data are required:

1. Pre-audit inventory and forecasts: a component-level inventory produced by the audit, listing for each relevant building element (e.g. partition type, ceiling system, cladding) its location, material composition, estimated quantities (m^2, m^3 or tonnes) and the foreseen management route (direct reuse, high-quality recycling, lower-grade recovery, or disposal).

2. Observed CDW flows during works: measured quantities of the same components and materials actually removed during deconstruction or demolition, typically obtained from weighbridge tickets, on-site sorting logs or CDW tracking forms. These data allow the calculation of deviations between audited and realised quantities, both for total waste and for the fraction that enters reuse or high-quality recycling streams.

3. Implementation evidence: qualitative and quantitative documentation that audit recommendations (e.g. selective dismantling sequences, segregation instructions, target recovery rates) were effectively implemented on site. This may include method statements, photographic records, contractor reports or compliance checks required under national CDW regulations and client specifications.

Using these data, the indicator can be expressed as one or more dimensionless scores that combine: (i) the existence of a formal pre-deconstruction audit; and (ii) the percentage deviation between predicted and actual quantities of reusable and recyclable materials. In the context of university campuses, this formulation captures how well pre-deconstruction audits are used not only as a documentation exercise but as an operational tool to secure high-quality recovery of building components, and thus to strengthen SBTool's coverage of end-of-life circularity mechanisms.

Measurability & Data Availability – score 2/5

In the GtoG project methodology from which this indicator is derived, the effectiveness of the pre-deconstruction audit (DT1) is evaluated through three sub-components: (i) the mere existence of a pre-deconstruction audit report (DT1.1); (ii) the percentage deviation between the total gypsum waste (GW) quantities forecast in the audit and the actual GW generated on site (DT1.2); and (iii) the deviation between the forecast and the realised quantities of recyclable GW (DT1.3). Effectiveness is achieved only when an audit exists and when deviations for total and recyclable GW fall below predefined thresholds (10% and 20%, respectively).

Operationalising this indicator therefore requires, for each project:

- a structured pre-deconstruction audit report containing a component-level inventory of gypsum-containing elements, their estimated quantities and their expected routing to reuse, high-quality recycling or lower-grade recovery.

- on-site monitoring data on the actual amounts of GW produced during demolition or refurbishment works; and
- weighbridge, recycling-plant or waste-acceptance records documenting how much of the GW stream has actually been routed to recycling or other treatments.

European guidance documents – notably the EU Construction and Demolition Waste Management Protocol, the EU Guidelines for the Waste Audits before Demolition and Renovation Works and the PARADE pre-demolition audit guidance – describe in detail how such audits should be performed and which information should be collected. However, they also emphasise that pre-demolition audits are applied only above nationally defined thresholds and are not yet routine for all demolition or refurbishment projects. Responsibility for requiring audits and setting thresholds is left to Member States and, in some cases, to local authorities, which leads to heterogeneous uptake and reporting practices across Europe. The European Environment Agency further notes that data on construction and demolition waste, including information on reuse and high-quality recycling, remain incomplete and methodologically inconsistent between countries, making it difficult to obtain robust, project-level datasets on material flows.

In the specific context of university campuses, this means that detailed pre-deconstruction audits and associated mass-flow data will only exist for a limited subset of buildings where major refurbishment or demolition has been planned under recent EU-aligned procedures. Historic building stock and routine renovation projects are unlikely to have comparable audit documentation, and the relevant information is rarely consolidated in centralised campus databases. Applying the DT1 indicator systematically across a campus would therefore require commissioning new audits and setting up dedicated measurement and recording processes, which goes beyond "business-as-usual" practice. For these reasons, while the indicator is technically measurable at project level when a full audit is carried out, its data availability at campus scale is low, and it is consequently scored 2/5 for Measurability & Data Availability.

Stakeholder Acceptance – score 3/5

The underlying idea of pre-deconstruction audits—systematically mapping building components before demolition in order to maximise reuse and high-quality recycling—is increasingly recognised in the literature as a promising circular-economy strategy for the construction sector (Ann et al., 2021; Giorgi et al., 2022). At the same time, empirical studies consistently show that audits are not yet embedded in everyday practice and are often perceived by clients and project teams as an additional burden in terms of time, cost and specialist expertise (Ann et al., 2021; Cárcel-Carrasco & Peñalvo-López, 2020). Reviews of circular-economy implementation and stakeholder behaviour in construction and demolition waste management highlight that many actors still have limited awareness of CE concepts, unclear responsibilities and insufficient incentives to invest in labour-intensive practices such as detailed audits, especially when they are not mandated by regulation (Giorgi et al., 2022; Munaro & Tavares, 2023; Zhao, 2021).

In a university-campus context, this means that sustainability offices and some technical staff are likely to appreciate the rationale of pre-deconstruction audits, particularly on flagship projects, but many facility managers, budget holders and contractors may still view them as "extra work" mainly relevant for waste managers rather than as a core element of campus asset management. The concept is therefore explainable and has clear potential to be accepted, yet it is not currently part of routine decision-making for most campus projects. For this reason, the indicator is rated 3/5 on Stakeholder Acceptance.

Policy/Market & Territorial Alignment – score 3/5

At European level, pre-demolition and pre-renovation audits are clearly embedded in the policy discussion on construction and demolition waste (CDW). The EU

Construction and Demolition Waste Management Protocol recommends that Member States and market actors use pre-demolition audits to identify materials, plan selective demolition and improve the quality of CDW streams for reuse and recycling (European Commission, 2016). The subsequent Guidelines for the Waste Audits before Demolition and Renovation Works of Buildings provide a more detailed procedure for such audits, explicitly linking them to the EU Circular Economy Package and to the broader resource-efficiency agenda in the building sector (European Commission, 2018). These documents signal a clear policy direction in favour of pre-deconstruction audits, even though they are presented as non-binding guidance rather than directly enforceable legislation (European Builders Confederation, 2022).

Beyond EU guidance, several market instruments and certification schemes also recognise pre-demolition audits. In the United Kingdom, for example, pre-demolition audits form part of the requirements within the BREEAM system and are used to support planning permissions, life cycle assessment and circular-economy statements (Akanbi et al., 2020; BRE, n.d.). This demonstrates that, in some advanced markets, pre-deconstruction audits are sufficiently institutionalised to influence both policy implementation and private certification practice.

In the Italian territorial context, however, the picture is more mixed. Analyses of national and regional frameworks indicate that pre-demolition audits are not yet mandatory at national level and are applied only in specific projects or local initiatives (Zanetti, 2019). Recent Italian work on circular economy in the construction sector confirms that the introduction and scaling-up of pre-demolition audit tools is still seen as a future requirement to improve traceability and reuse of CDW, rather than as a fully established practice (Giorgi, 2024). For university campuses, which are typically subject to standard public procurement rules but not to additional voluntary requirements, this means that pre-deconstruction audits are encouraged by EU policy and by best-practice guidance, yet they are not systematically required or routinely implemented.

Overall, the indicator shows good alignment with the EU policy direction and with emerging market practices, but this alignment is not yet strong or widespread in the specific Italian university context. For this reason, Effectiveness of Pre-Deconstruction Audit is assigned a score of 3/5 for Policy/Market & Territorial Alignment.

Circularity Impact – score 5/5

When implemented, an effective pre-deconstruction audit has a very high potential to close resource loops. It identifies reusable components and recyclable fractions, links them to local markets and recycling capacity, and supports selective deconstruction instead of conventional demolition. Empirical studies show that pre-demolition audits can significantly increase reuse and recycling rates for construction and demolition waste, thereby reducing landfilling and demand for virgin materials. Because this indicator directly targets high-value reuse and high-quality recycling at end-of-life, it is rated 5 for Circularity Impact.

Integration Feasibility & Essentiality – score 3/5

From an integration viewpoint, the Effectiveness of Pre-Deconstruction Audit indicator fits naturally within SBTool/ITACA's C. Resource Management – C3. Materials Management – C3.4 Design for deconstruction area, where it can complement existing criteria on design for disassembly and construction-and-demolition waste (CDW) management. Recent European work on common building indicators, including the JRC study on life-cycle environmental performance and the development of the Level(s) framework, emphasises that assessment schemes should use a coherent set of indicators to support "resource-efficient material life cycles" and facilitate future reuse and high-quality recycling of construction products (Dodd et al., 2016; Dodd et al., 2017).

In practical terms, the indicator can be implemented as a quantitative KPI that records whether a pre-deconstruction audit has been carried out for major renovation or demolition works and to what extent its recommendations are implemented. The audit output (inventories of reusable components, estimated quantities for high-quality recycling and actual recovery rates) can be normalised by gross floor area or total mass and expressed in the same units as existing CDW indicators (e.g. kg/m² or percentage of total CDW). This alignment of units and life-cycle stage makes it technically feasible to embed the indicator in SBTool's scoring structure, provided that clear rules are defined to avoid double counting with existing criteria on CDW diversion and recycled content.

Regarding essentiality, pre-deconstruction audits address a recognised gap in current assessment schemes. The JRC working paper on building indicators notes that, although certification systems such as BREEAM and DGNB reward design-for-deconstruction practices, they often lack clear, operational frameworks for assessing how such practices translate into actual material recovery at end-of-life (Dodd et al., 2016, pp. 3614–3624). An indicator that evaluates the effectiveness of pre-deconstruction audits would therefore strengthen SBTool's coverage of end-of-life circularity by explicitly linking building assessment to the planning and realisation of reuse and high-quality recycling. At the same time, its essentiality for a campus-wide SBTool application is moderated by its limited scope: the indicator is only activated in projects that reach a major refurbishment or demolition phase and depends strongly on national requirements and local CDW markets. In contexts where audits are not mandated or are rarely performed, the indicator would remain unused for long periods, and existing SBTool criteria on CDW management already cover part of its intent. For these reasons, its contribution is judged important but not foundational for all campus buildings, leading to a moderate score of 3/5 for Integration Feasibility & Essentiality.

Evidence Strength – score 4/5

The evidence base for pre-demolition/pre-deconstruction audits is relatively strong at both policy and research levels. At European level, the EU Construction & Demolition Waste Management Protocol and the Guidelines for the waste audits before demolition and renovation works of buildings set out audit procedures and explicitly link them to improved quality of construction and demolition waste (CDW) and higher reuse and recycling rates. These documents position waste audits as a key action under the Circular Economy Action Plan, indicating that the concept is embedded in the EU's strategic approach to CDW management.

Academic and technical studies provide further support. Work within the GtoG (Gypsum-to-Gypsum) project developed performance indicators to monitor end-of-life gypsum flows and demonstrated that pre-deconstruction diagnostics and audits are necessary to enable closed-loop recycling of plasterboard waste. Case studies from different European contexts show that pre-demolition or pre-renovation audits can increase recovery rates and improve the quality of secondary materials. For example, Spišáková et al. (2021) documented, through a detailed audit of a shopping centre refurbishment, how waste audits allow better separation of CDW streams and can also yield clear economic benefits compared with "business-as-usual" disposal routes. Similarly, several empirical works on refurbishment and pre-refurbishment audits report that early auditing supports more systematic planning of reuse and high-quality recycling strategies on site.

Beyond single case studies, reviews of CDW management practices in Europe emphasise pre-demolition audits as one of the core best practices for achieving higher recovery rates and implementing circular economy principles in the construction sector. Gálvez-Martos et al. (2018), for instance, identify waste audits as part of an integrated set of measures needed to move towards best practice CDW management across the value chain. This combination of EU-level guidance, sectoral projects (such as GtoG) and peer-reviewed empirical research provides a solid conceptual and practical foundation for using the Effectiveness of Pre-Deconstruction Audit as a circularity indicator.

At the same time, the evidence is not yet fully standardised across all Member States: methodologies, indicator definitions and implementation rates still vary by country and by project type, and most documented applications focus on specific building typologies or materials. For this reason, the evidence is assessed as robust but not completely consolidated, which justifies a relatively high but not maximum score of 4/5 for Evidence Strength.

4.3.5 AHP-weighted comparison and final selection

This subsection brings together the results of the previous steps to identify the single SBTool gap indicator that will be further developed and tested in the DRH case study. The two shortlisted indicators—Durability & Replacement Cycles and Effectiveness of Pre-Deconstruction Audit—were qualitatively assessed against the six evaluation criteria defined in the evaluation framework (Section 3.9) and scored on a 1–5 scale using the rubric presented there. These scores were then combined with the criterion weights reported in Section 4.3.2, in order to derive a transparent, quantitative ranking.

Table 22 summarises the synthesis step. For each criterion, it reports: (i) the AHP weight; (ii) the 1–5 score assigned to each indicator; and (iii) the resulting weighted contribution, calculated as the product of the weight and the score. The total weighted score for each indicator is obtained by summing its six weighted contributions.

Table 22. AHP-weighted evaluation of the two shortlisted indicators

Criterion	Weight	Durability & Replacement Cycles – score	Durability – weighted contribution	Pre-Deconstruction Audit – score	Pre-Deconstruction – weighted contribution
Measurability & Data Availability	0.214	4	0.856	2	0.428
Stakeholder Acceptance	0.199	4	0.796	3	0.597
Policy/Market & Territorial Alignment	0.199	4	0.796	3	0.597
Circularity Impact	0.180	4	0.720	5	0.900
Integration Feasibility & Essentiality	0.114	5	0.570	3	0.342
Evidence Strength	0.094	4	0.376	4	0.376
Total weighted score			4.11		3.24

The AHP-weighted totals show that Durability & Replacement Cycles achieves a higher overall score (4.11/5) than Effectiveness of Pre-Deconstruction Audit (3.24/5). This result reflects the different profiles of the two indicators with respect to the weighted criteria.

Durability & Replacement Cycles performs strongly on the three criteria that Delphi and AHP identified as particularly important—Measurability & Data Availability, Stakeholder Acceptance and Policy/Market & Territorial Alignment—and it also has a high score on Integration Feasibility & Essentiality. As discussed in previous sections, the necessary data can largely be obtained from standard campus documentation, the concept is easily understood by campus stakeholders, it aligns well with international service-life and life-cycle frameworks and it can be integrated into SBTool/ITACA as a quantitative reinforcement of the existing “Service Quality / Optimisation and Maintenance” area at category/issue level. The indicator also shows good Circularity Impact, by directly operationalising the “slow” loop through longer service lives and fewer replacement cycles, and solid Evidence Strength based on service-life and LCA literature.

Effectiveness of Pre-Deconstruction Audit, by contrast, attains a very high score on Circularity Impact and a similarly strong score on Evidence Strength, since pre-demolition audits are clearly recognised in EU guidance and in sectoral research as an effective way to increase reuse and high-quality recycling of construction and demolition waste. However, its performance on Measurability & Data Availability and Policy/Market & Territorial Alignment is lower: detailed audit and mass-flow data are only available for a limited number of projects, and pre-demolition audits are not yet a routine requirement in the Italian university context. Its Integration Feasibility & Essentiality is also moderate, as the indicator targets a relatively narrow life-cycle stage (major renovation or demolition) and depends strongly on national regulatory frameworks and local CDW markets.

Because the AHP weights give relatively high importance to feasibility- and context-related criteria (Measurability, Stakeholder Acceptance, Policy/Market & Territorial Alignment), these differences translate into a clear advantage for Durability & Replacement Cycles in the overall ranking. While Effectiveness of Pre-Deconstruction Audit remains a valuable and highly impactful end-of-life indicator, its current applicability and institutional anchoring at campus scale are not yet sufficient to justify its selection as the single key gap indicator in this thesis.

On the basis of this synthesis, Durability & Replacement Cycles is selected as the key SBTool gap indicator. It is judged to best meet the two core requirements defined at the beginning of the chapter: (i) contributing meaningfully to the sustainability performance of university campuses, and (ii) strengthening SBTool at category/issue level by explicitly representing a circular-economy mechanism—service-life extension and reduced replacement frequency—that is currently only implicitly addressed. The next chapter will therefore focus on the operationalisation of this indicator within the SBTool/ITACA framework and on its application to the Digital Revolution House case study.

Chapter 5. Proposed Modifications to SBTool (Gap Indicator)

This section develops the Durability & Replacement Cycles indicator as a proposed enhancement to SBTool/ITACA, following the service-life oriented logic adopted in the reference literature and adapting it to the specific context of university campus buildings. The Durability & Replacement Cycles indicator proposed in this thesis is derived from the approach used by Paiva et al. (2022), where the number of mortar replacements over a 50-year reference period is treated as a key variable in life cycle GHG emissions assessment. In their study, alternative service-life scenarios (one, two or three replacements) are used to show how strongly replacement frequency influences the overall climate-change impact of plastering mortars. Building on this logic, the present work extends the 'number of replacements over 50 years' concept from a single material layer to a set of campus-relevant components, aggregating them into a building-level KPI that can be integrated into SBTool/ITACA.

5.1 Rationale for CE-aligned enhancement of SBTool/ITACA

In circular-economy terms, strategies for the built environment do not only "close" material loops at end-of-life; they also "slow" loops by extending the service life of building components and reducing the frequency of replacements. For long-lived, high-use assets such as university campuses, this "slow-loop" dimension is particularly relevant: envelope systems, interior finishes and technical services are often replaced multiple times over the campus lifetime, with significant implications for resource demand, waste generation, life-cycle emissions and operating budgets.

The mapping exercise in Chapter 3 showed that SBTool/ITACA already addresses aspects of maintenance, adaptability and disassembly, but does so mainly through qualitative criteria and checklists. What is currently missing is a quantitative KPI that explicitly captures how often components are replaced over a reference period. At the same time, the literature on component-level LCA, such as the work on low-impact mortars and other building elements, shows that assumptions on service life and the number of replacements can drastically change life-cycle environmental results, even when the materials themselves are relatively low impact. In LCA terms, this is reflected in the strong contribution of module B4 (replacement) to the overall GWP of short-lived components.

Introducing a Durability & Replacement Cycles indicator into SBTool/ITACA therefore responds to a clear gap identified in the thesis:

- it makes the “slow loop” of circularity (longer service lives, fewer replacements) visible and measurable.
- it allows SBTool/ITACA to distinguish between buildings that minimise replacement demand and those that rely on frequent, material-intensive refurbishment; and
- it provides an explicit bridge between service-life planning (ISO 15686) and building-level sustainability assessment, without requiring a full LCA for every project.

For university owners and campus managers, this additional criterion can inform refurbishment strategies, maintenance planning and procurement by highlighting solutions that reduce replacement frequency, thereby contributing simultaneously to circularity and life-cycle cost optimisation.

5.2 Durability and replacement cycles: concept and scope

In the context of this research, durability denotes the capacity of a building component or system to maintain its required performance over time under specified conditions of use and maintenance. The associated service life is the period during which this performance is expected to be achieved without full replacement.

The Durability & Replacement Cycles indicator expresses, in aggregated form, how frequently components are renewed within a defined reference period. Consistent with current practice in building life-cycle assessment, this period is set to 50 years. The indicator is first determined at the component level, assigning to each component type a number of replacements over the 50-year horizon, and is then aggregated into a single building-level index suitable for integration into SBTool/ITACA.

The scope of the indicator is intentionally selective. It is applied only to components that make up a non-negligible share of the building stock, are expected to undergo one or more full replacements during the reference period and have a service life that can be estimated with acceptable reliability on the basis of standards, technical literature or established practice. Under these conditions, the relevant set of elements in campus buildings is essentially limited to the building envelope, interior finishes and a group of technical systems for which replacement cycles are well documented, notably lighting equipment and HVAC terminal units. Primary structural elements, such as reinforced-concrete or main steel frames, are excluded, since their service lives typically extend beyond the 50-year reference period and their circularity performance is more appropriately captured through other criteria (for example deconstructability, reuse potential or structural adaptability).

Methodologically, the indicator is compatible with established service-life planning frameworks, such as ISO 15686, and with the representation of replacement in building LCA standards, such as EN 15978 and EN 15804 (module B4). Its role is not to quantify environmental impacts directly, but rather to provide a transparent measure of replacement frequency that can be combined, where required, with environmental or cost data in complementary analyses. The overall structure of the indicator is summarised in Figure 18, which illustrates the passage from component-level replacement counts, through a set of eligibility conditions, to a building-level KPI and shows the main families of campus components included within the scope.

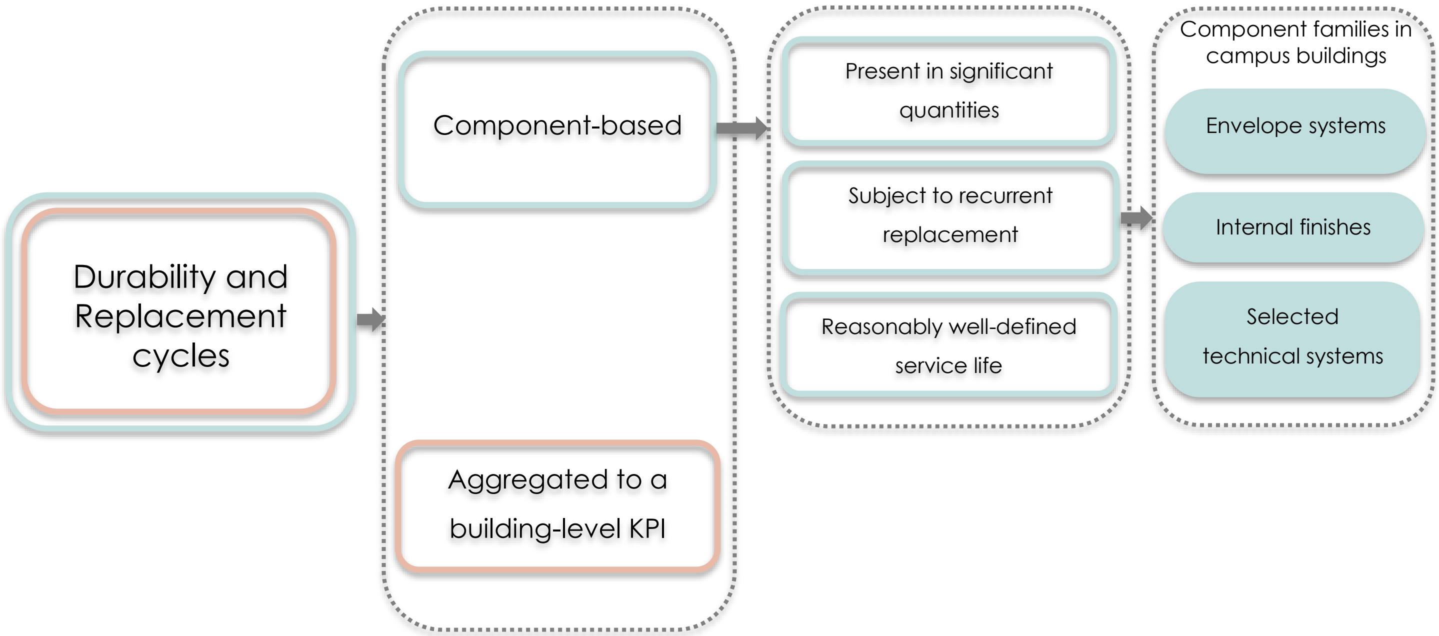


Figure 19. Conceptual structure of the Durability & Replacement Cycles indicator and its scope in campus buildings.

5.3 KPI and scoring rules

The proposed KPI captures the intensity of replacement cycles over the building envelope, weighted by the relative area occupied by each component type.

For each component type i, with:

- reference service life SL_i (years), and
- reference period T_{ref} (years),

the number of full replacements is defined as:

$$N_{\text{rep},i} = \lfloor \frac{T_{\text{ref}}}{SL_i} \rfloor$$

where $N_{\text{rep},i}$ represents the number of complete replacement cycles over the reference period (excluding the initial installation). The use of the floor function keeps the indicator conservative and avoids fractional replacements, in line with the fact that maintenance planning normally works with whole interventions.

To obtain a building-level index, $N_{\text{rep},i}$ is aggregated across all n selected component types using a weighting factor w_i that reflects their relative importance. In this thesis, area-based weighting is adopted as a pragmatic default.

For each component type i:

- **Area of component i**

$$A_i[\text{m}^2]$$

- **Total envelope area**

$$A_{\text{env}} = \sum_{i=1}^{n} A_i$$

- **Percentage (share) of envelope occupied by i**

$$w_i = \frac{A_i}{A_{\text{env}}}$$

The Durability & Replacement Cycles index for the building is then computed as an area-weighted average:

$$DR_{\text{building}} = \sum_{i=1}^{n} w_i \cdot N_{\text{rep},i}$$

Each term $w_i \cdot N_{\text{rep},i}$ represents the contribution of component i to the average number of replacement cycles per square metre of envelope. Summing these contributions yields the average number of full replacements per square metre of envelope over the reference period (50 years in this thesis). A lower value of DR_{building} indicates a more durable building, with fewer replacement cycles per unit area; a higher value indicates more frequent replacements, especially when affecting large-area components.

For use within SBTool/ITACA, this continuous value is translated into a five-point score consistent with the existing scoring logic. As a first approximation, the following conceptual bands are proposed:

- buildings with very low replacement intensity (e.g. $DR_{\text{building}} \leq 1.0$) receive the maximum score.
- buildings with very high replacement intensity (e.g. $DR_{\text{building}} \geq 3.0$) receive the minimum score.
- intermediate bands are defined by stepwise thresholds between these anchors.

In this pilot application, the mapping between DR_{building} and the SBTool/ITACA score is defined as follows (for $T_{\text{ref}} = 50$years):

Table 23- Proposed scoring bands for the Durability & Replacement Cycles index (DR_building), with corresponding durability interpretation and SBTool-style score.

DR_building (50 years)	**Durability interpretation**	**SBTool-style score**
≤ 1.0	very high durability	+5

DR_building (50 years)	Durability interpretation	SBTool-style score
1.0 – 1.5	high durability	+3
1.5 – 2.0	medium durability	+1
2.0 – 3.0	low durability	0
≥ 3.0	very low durability (many replacements)	−1

In future applications of SBTool/ITACA, these thresholds should be refined and tested on a larger sample of campus buildings (and adjusted if a different reference period is adopted). In this thesis, they are used as indicative pilot values to demonstrate how the durability indicator can be integrated into the scoring system.

5.4 Reporting boundary and data requirements

The reporting boundary of the Durability & Replacement Cycles indicator corresponds to the use-stage module B4 (replacement) over the chosen reference period. The indicator itself does not quantify environmental impacts; rather, it provides a frequency metric that can subsequently be used as input to environmental or cost assessments, where required.

To compute the KPI for a given building, three main data sets are required and are summarised in Table 18. The first data set is the component inventory, which provides a structured list of all components included in the indicator. Each component type is characterised by a unique identifier, a concise description, its location and function within the building, and its quantity. Quantities are expressed in appropriate units, typically square metres for surface elements or number of units for discrete elements, and are derived from architectural drawings, quantity take-offs, BIM schedules or as-built documentation. The use of consistent identifiers and units across the assessment ensures that components can be traced and aggregated in a transparent manner.

The second data set concerns the reference service lives of the selected components. For each component type, an expected service life under typical campus conditions is specified, together with the source of this value. In practice, these service lives are taken from service-life planning standards and handbooks (such as ISO 15686 and national adaptations), technical guidelines and manufacturers' documentation, and empirical literature on component durability. Where multiple sources provide different values, a range can be recorded and a final adopted value is chosen on a conservative basis, with the underlying judgement briefly documented. This approach makes the assumptions behind the indicator explicit and auditable.

The third data set defines the global parameters used to calculate and aggregate the indicator: the reference period and the weighting factors. The study period T_{ref} represents the time horizon over which replacement cycles are counted and should be consistent with the life-cycle perspective used elsewhere in SBTool/ITACA. In this thesis it is set to 50 years, in line with common practice in building LCA and with SBTool/ITACA life-cycle assumptions. The weighting scheme specifies the aggregation logic at building level. Area-based weighting is adopted as the baseline, so that each component weight w_i corresponds to its area A_i; alternative options, such as cost-based or impact-based weights, can be explored in further applications. Where useful for interpretation, weights may also be normalised to express the relative contribution of each component to the overall index.

This data structure is intentionally generic so that it can be applied to any campus building. In practice, the underlying quantities and service lives may be obtained from BIM models, detailed quantity take-offs or conventional design documentation, but the definition of the indicator itself remains tool neutral. The detailed operationalisation for the DRH pilot, including the specific component series is presented in Chapter 6.

Table 24. Required input data for the Durability & Replacement Cycles indicator.

Data set	Data item / field	Description	Typical unit / format	Typical sources / notes
Component inventory	Component ID	Unique identifier for each component type included in the indicator.	Text / code (e.g. M1, S2, W3)	Defined by the assessor or BIM/CAE environment; must be consistent across tables and figures.
	Component description	Concise description of the component type.	Text	e.g. "External wall – ventilated cladding", "Flat roof waterproofing", "Aluminium-framed double-glazed window".
	Location / function	Main position and role of the component in the building.	Text	e.g. "External wall – north façade", "Roof covering over lecture halls", "Window type A – teaching spaces".
	Quantity	Extent of the component in the building.	m² (surfaces) / no. of units (discrete)	Derived from drawings, quantity take-offs, BIM schedules or as-built documentation.
	Quantity unit	Measurement unit used for the quantity.	m², m, no. of units, etc.	Choose a consistent unit per component family (e.g. m² for surfaces, number of units for luminaires and fan-coils).
Reference service lives	Reference service life (SL_i)	Expected service life of the component under typical campus use and maintenance.	Years	Taken from service-life planning standards and handbooks (e.g. ISO 15686 and national adaptations), technical guidelines and manufacturers' documentation, and relevant empirical literature on component durability.
	Source of (SL_i)	Reference used to justify the chosen service life value.	Text / bibliographic reference	Cite standard, guideline, technical datasheet or literature reference; specify edition or year where relevant.
	Service-life range (if any)	Minimum and maximum values reported in the sources (where applicable).	Years (min–max)	Used when multiple sources provide different values; supports transparent choice of a conservative value.
	Adopted (SL_i)	Final service life used in the calculation, derived from available ranges and expert judgement.	Years	Where there is uncertainty, the conservative assumption should be selected and briefly justified in a note.
Reference period & weights	Reference period (T_{ref})	Study period over which replacement cycles are counted; should match the life-cycle perspective in SBTool/ITACA.	Years	In this thesis set to 50 years, consistent with common practice in building LCA and SBTool/ITACA life-cycle assumptions.
	Weighting basis	Principle used to weight components in the building-level aggregation.	Text	Area-based weighting (m²) is recommended as baseline; alternative options include cost-based or impact-based weighting.
	Component weight (w_i)	Numerical weight assigned to component i according to the selected basis.	m², €, kgCO₂e, or dimensionless share	For area-based weighting, (w_i = A_i). For cost- or impact-based weighting, (w_i) would reflect component cost or embodied impact; these options can be explored in further applications beyond the scope of this thesis.
	Normalised weight (w_i / \sum w_i)	Share of each component in total weighting, used for interpretation and	Dimensionless (0–1) or %	Not strictly required for the KPI calculation, but useful to illustrate which components dominate the building-level index and to

Data set	Data item / field	Description	Typical unit / format	Typical sources / notes
	(optional)	comparison between buildings.		support sensitivity analyses.

5.5 Placement within SBTool/ITACA (Issue → Category→ Criterion)

Within the SBTool/ITACA framework the proposed Durability & Replacement Cycles indicator is located in Issue E – Service Quality / Management, as a new criterion in the category devoted to Optimization and Maintenance of Operating Performance. Issue E already groups criteria that describe how the building performs in use, how easily it can be operated and maintained and how its service conditions are managed over time. However, the current set of criteria is predominantly qualitative: they assess, for instance, whether systems are accessible for maintenance and whether operating conditions can be effectively controlled, but they do not quantify how often envelope systems, finishes or technical services are expected to be replaced within the reference period. The Durability & Replacement Cycles indicator is intended to fill this gap by introducing an explicitly quantitative description of replacement frequency while remaining within the same conceptual family of long-term service quality and management.

The decision to place the indicator within the existing Optimization and Maintenance category, instead of creating a separate "Durability" category, is motivated by both methodological and practical considerations. From a methodological standpoint, replacement cycles are a long-term outcome of design choices and maintenance regimes: more durable components and appropriate maintenance strategies reduce the number of full replacements required over 50 years, thereby optimising operating performance and limiting disruption for users. In this sense, durability is one of the principal levers through which optimisation and maintenance objectives are pursued. From a practical standpoint, the ITACA protocol is organised in a hierarchical tree of

Issues, categories and criteria with established weights; extending the protocol by adding new criteria within existing categories is consistent with previous adaptations and avoids the need to reconfigure weights and scoring structures across the whole tool.

Locating the Durability & Replacement Cycles criterion in Issue E also keeps it clearly distinct from energy and environmental load criteria, which are concentrated in the energy and resources and environmental loading areas and are usually expressed as impacts per square metre or per functional unit. The new criterion is a frequency metric, expressed as the average number of full replacements over a 50-year period, and does not itself quantify environmental loads or costs. This separation prevents double counting when the indicator is used alongside life-cycle assessment or life-cycle cost modules, while still allowing the replacement factors derived here to be used as inputs for module B4 in LCA or for long-term budget planning.

At the same time, the criterion is designed to complement existing SBTool/ITACA provisions on disassembly, adaptability and maintainability rather than to duplicate them. Qualitative checks on ease of access, dismountability or flexibility of space remain necessary, but they are now accompanied by a quantitative measure of how frequently the main components are renewed over the reference period. A campus building that is easy to maintain but requires frequent replacement of short-lived finishes will receive a different durability score from one that combines good maintainability with long service lives; this distinction is currently invisible in the protocol and is exactly what the new indicator is intended to reveal.

The proposed placement is illustrated in Figure 19, which presents a mini SBTool/ITACA card for the criterion. The figure shows the link to Isuue E – Service Quality / Management and Category E4 – Optimization and Maintenance of Operating Performance, states the objective ("to limit the frequency of replacements over the 50-year reference period by promoting durable components and appropriate maintenance in campus buildings"), and summarises the main elements of the criterion: the KPI $DR_{building}$, its unit (average number of replacements over 50 years) and the component families in scope (envelope systems, interior finishes and selected

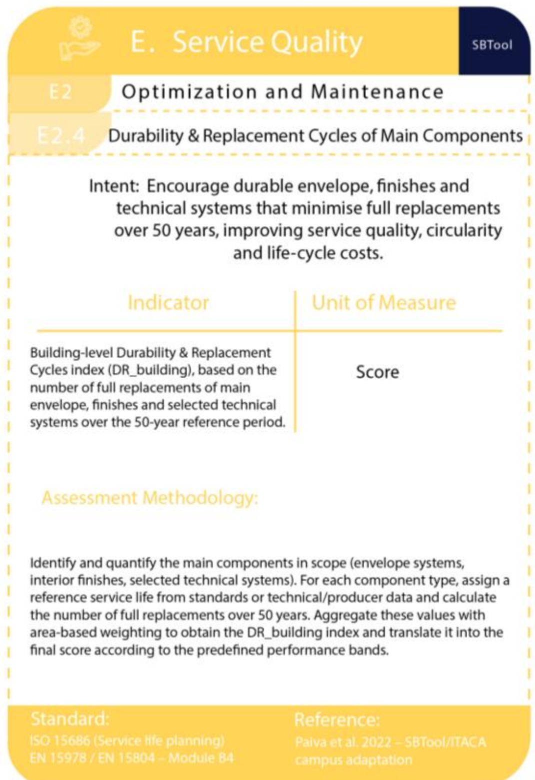


Figure 20. SBTool mini card for criterion E2.4 “Durability & Replacement Cycles of Main Components”

technical systems). In this way, the figure makes explicit that the Durability & Replacement Cycles indicator is conceived as a targeted, CE-aligned enhancement that can be integrated into the existing SBTool/ITACA hierarchy without altering its fundamental structure.

5.6 Integration rules (boundaries, data, avoiding double counting)

To integrate the Durability & Replacement Cycles indicator into SBTool/ITACA in a consistent way, a set of basic integration rules is required. These rules are not prescribed by existing standards but derive directly from the definition of the indicator and from the need to avoid double counting when it is used together with other performance metrics.

First, the indicator is conceived as a frequency metric and is therefore kept separate from environmental or economic impact indicators. The value $DR_{building}$expresses the average number of full replacements of key components over the 50-year reference period and does not, by itself, quantify emissions or costs. When a life-cycle assessment is carried out in parallel, the replacement factors $N_{rep,i}$derived for the indicator can be used as input to module B4, but the resulting environmental impacts are not fed back into the durability score. In this way the same phenomenon – replacement of components – is represented once as a frequency (for SBTool/ITACA scoring) and once as an impact (for LCA), without being counted twice in the overall assessment.

Second, the indicator must be based on a clearly defined scope and reference period. Each application has to specify which components are included in the inventory and which study period is adopted. If different projects use different component sets or different reference periods, the resulting values of $DR_{building}$are not directly comparable and should not be combined in the same benchmarking set. This rule ensures that comparisons between campus buildings reflect genuine differences in durability and replacement patterns, rather than differences in system boundaries.

Third, the service-life assumptions used in the assessment must be internally consistent. The same set of reference service lives should underlie both the calculation of replacement cycles and any parallel LCA or LCC analyses. Using one set of service-life values to adjust embodied-impact results and a different set to generate the durability score would introduce hidden inconsistencies; using the same values twice in a way that mechanically couples the durability score and the impact indicators would risk double counting unless this relationship is explicitly modelled and justified. In the present thesis, to keep the approach transparent, the Durability & Replacement Cycles indicator is used as an independent KPI that is interpreted qualitatively alongside existing SBTool/ITACA criteria, without any numerical aggregation with energy or LCA scores.

Overall, these integration rules act as methodological "guardrails" that define how the new indicator can be combined with the existing SBTool/ITACA framework and with life-cycle analyses, ensuring that its contribution to the assessment is both interpretable and free from unintended overlaps.

Table 25. Durability & Replacement Cycles Integration rules

Rule no.	Integration rule	Rationale / what it avoids	Practical implication for assessment
1	Treat (DR_{building}) as a frequency metric, separate from impact indicators	Replacement cycles are represented once as "how often replacements occur", not as emissions or costs, avoiding double counting with LCA/LCC results.	Use (N_{rep,i}) and (DR_{building}) only to describe durability. If an LCA is performed, the same (N_{rep,i}) values may be used as input for module B4, but their impacts are not reintroduced into the durability score.
2	Apply a clearly defined scope and reference period	Ensures comparability between buildings and prevents artificial differences caused by inconsistent system boundaries.	For each assessment, explicitly state which component families are included and the reference period (here (T_{ref} = 50) years). Do not benchmark buildings that use different scopes or reference periods in the same comparison set.
3	Use consistent service-life assumptions across all modules and keep the indicator as an independent KPI	Avoids hidden inconsistencies or double use of service-life data when both durability and LCA/LCC are performed.	Base both the durability indicator and any parallel LCA/LCC on the same set of reference service lives. Interpret (DR_{building}) qualitatively alongside energy and LCA scores, without direct numerical aggregation unless an explicit combined model is developed and justified.

5.7 Expected benefits and limitations

The main expected benefit of introducing the Durability & Replacement Cycles indicator is that it makes the long-term replacement burden of campus buildings visible and comparable. It allows SBTool/ITACA to distinguish buildings that rely on durable envelope systems, robust finishes and long-lasting services from those that require frequent interventions, even when both meet the same operational energy targets. For university owners, this supports more informed decisions about refurbishment strategies, maintenance plans and procurement of components with longer service lives, contributing to both circularity (slow loops) and lifecycle cost optimisation. At methodological level, the indicator aligns SBTool with the life-cycle logic of existing LCA standards and EU frameworks, without imposing complex data requirements.

At the same time, the indicator has limitations. It depends on assumed service-life values, which may vary between sources and can be optimistic if not calibrated against local experience. It captures the frequency of replacements, but not the quality of the maintenance regime or the environmental profile of the replacement products. In addition, the DRH pilot relies on reference service lives rather than on observed campus maintenance records, given the recent construction of the building. These limitations do not undermine the value of the indicator as a first, operational step towards integrating durability into SBTool/ITACA, but they should be acknowledged and addressed in future work through calibration on larger samples of campus buildings and, where possible, linkage with empirical maintenance data.

Chapter 6. Case Study Application: DRH (Politecnico di Torino)

6.1 Recap of the DRH case-study framework

Chapter 3 introduced the Digital Revolution House (DRH) as a recent, high-performance addition to the Politecnico di Torino campus, developed through a partnership between Fondazione CRT, the Politecnico and the Italian Institute for Artificial Intelligence (AI4I). Functionally, the building concentrates a continuum of activities ranging from experimental student projects in the Casa dei Team, to advanced training at level P01, up to departmental, interdepartmental and excellence research centres on the upper floors. From a sustainability perspective, DRH is designed as a nearly zero-energy building (NZEB, class A4), compliant with CAM requirements and certified under the ITACA Regione Piemonte – Edifici non residenziali 2018 protocol, with an overall score of 2.3 and documented attention to recycled, renewable and certified materials.

Chapter 3 also highlighted that DRH is supported by an exceptionally robust documentary base: a complete set of executive drawings and stratigraphy abaci, ITACA and CAM technical reports, EDILCLIMA energy simulations, specialist comfort and acoustic studies, quantity take-offs and a project-wide material inventory compiled for ITACA criteria B4.6 and B4.7. Criterion E6.5 further commits the Politecnico di Torino to archiving these documents and the as-built BIM model for the whole building life cycle. Together, these elements make DRH an appropriate and well-documented test bed for the Durability & Replacement Cycles indicator developed in this chapter.

Building on this framework, the following sections first focus on the construction and organisation of the DRH envelope and then clarify the scope of the durability assessment, which is deliberately restricted to envelope components. Interior elements are discussed mainly in terms of adaptability and deconstructability, reflecting their role in accommodating future functional changes in a university-campus context.

6.2 From whole building to envelope focus

6.2.1 Summary of DRH construction systems

From a construction standpoint, the Digital Revolution House is a reinforced-concrete building founded on a 1.00 m thick raft slab at approximately –6.20 m relative to the ground-floor reference level. Excavation is retained on three sides by "Berlin-type" walls of steel micropiles with internal inclined struts, due to the limited working space and the proximity of the former Officine Nebiolo and the historic underground air-raid shelter. The raft foundation is mechanically connected to the foundations of the existing Energy Centre and preserves the existing wastewater collection and pumping systems (Politecnico di Torino – Area Edilizia e Logistica, 2021, 2022).

The vertical structure consists of reinforced-concrete columns and shear walls: seismic actions are resisted by the shear walls, while columns carry vertical loads and accommodate lateral displacements. Floor slabs are solid 30 cm reinforced-concrete plates, dimensioned for relatively high variable loads (from 3 kN/m² on technical terraces up to 20 kN/m² in external areas at level P00), reflecting the mixed research, teaching and technical uses of the building.

Internally, construction and finishes follow a robust, low-maintenance logic appropriate for an intensively used university building. Technical rooms, storage areas and the underground car park use concrete floors with hard-wearing surface layers and blockwork walls with exposed services. In the Casa dei Team, floors are finished with high-strength resin and services are left visible beneath the slab, with mineral-wool and wood-wool linings improving acoustic comfort. Teaching and research levels (P01–P04) adopt floating modular floors with bamboo finish over impact-sound insulation, dry linings for service distribution, and suspended radiant or perforated metal ceilings in classrooms and open-plan workspaces.

The thermo-mechanical system differentiates emission types by zone: fan-coil units with primary air in laboratories and workshops, radiant floors with primary air in the atrium and associated spaces, and radiant ceilings with primary air in teaching and research areas. A groundwater-fed heat-pump plant in the basement supplies hot and chilled water via the existing wells serving the Energy Centre, and the building shares with it several key infrastructures, including medium-voltage power supply, groundwater intake, fire-fighting systems, stormwater management and rainwater reuse. A 117.78 kWp photovoltaic installation on terraces and technical roofs contributes to the NZEB energy profile (Politecnico di Torino – Area Edilizia e Logistica, 2021, 2022; Politecnico di Torino, n.d.).

Against this background, the remainder of the chapter narrows the focus from the overall construction system to the building envelope, which constitutes the main object of the Durability & Replacement Cycles indicator.

6.2.2 Building envelope and façade systems of DRH

The DRH envelope is designed as a modular, high-performance system that combines thermal efficiency, solar control and formal coherence with the adjacent Energy Centre. The main volume is a linear bar aligned with Via Paolo Borsellino, with its most exposed fronts facing the internal garden (south-west) and the Ex Nebiolo-building (north-east). The façades follow a 1.25 m module coordinated with the structural grid, which facilitates repetition of components and the definition of homogeneous durability classes.

Glazed façades and curtain walls

Transparent portions of the long elevations are realised as continuous aluminium curtain walls with thermal breaks and double glazing. Opaque aluminium spandrel panels are inserted where necessary to cover floor edges and to comply with fire-safety requirements. In the durability analysis, these curtain-wall fields constitute a primary envelope family, as they combine multiple sub-components (frames, gaskets, coatings, sealants, glazing and anchoring brackets) exposed to solar radiation, wind and driving rain.

Opaque walls and ventilated cladding

Opaque façade sections, corresponding mainly to stairs and service blocks, are built in lightweight concrete block masonry with external thermal insulation and render where external shading structures are present. In more exposed zones, the outer layer is an aluminium micro-ventilated façade mounted on a secondary metal substructure. The combination of insulated masonry, ventilated cavity and metal cladding defines a second major envelope family, with distinct durability and replacement patterns for the masonry substrate, the external insulation, the substructure and the metal panels.

Loggias and solar-shading systems

On the south-west elevation, deep framed loggias articulate the volume and provide outdoor extensions of teaching and research spaces. On the long south-east and north-west façades, solar-shading devices are detached from the façade plane and supported by hot-dip-galvanised steel structures that also carry metal-grating maintenance walkways. Fixed wooden fins (“palette”) with constant spacing and length are aligned with the façade module, while their depth and inclination vary according to simulation studies to balance daylighting and solar gains. On the short façades a shallower, continuous shading frame is placed closer to the façade surface. These systems introduce additional components—steel frames, grating, timber fins, fixings and protective finishes—whose durability is particularly sensitive to exposure, maintenance quality and protective treatments.

Roof terrace, technical volume and external works

At roof level, the technical volume housing air-handling units and other plant is clad in pre-insulated metal sheeting, and flat roofs host the photovoltaic arrays and technical walkways. External paved areas around the building use high-albedo concrete blocks over structural sub-bases, while green areas are laid as lawn over a multilayer build-up with filtration, drainage and anti-root protections connected to the existing rainwater-reuse system. Although only some of these external works are directly included in the quantitative durability indicator, they are important for understanding the exposure, accessibility and maintenance conditions of the envelope (for instance, the presence of maintenance walkways and safe access to shading structures and façade panels).

On this basis, the DRH envelope is decomposed in the following sections into a limited number of component families—curtain walls, insulated opaque façades, ventilated cladding, loggia assemblies, solar-shading systems, roof build-ups and metal cladding to technical volumes—each associated with specific exposure conditions and service-life assumptions.

6.2.3 Why the indicator concentrates on the envelope

Although the Digital Revolution House includes a wide range of internal finishes and building-services components, the quantitative Durability & Replacement Cycles indicator is, in this thesis, applied primarily to the envelope. This focus reflects both the functional profile of DRH as a university building and the methodological objectives of the indicator.

Within a campus context, interior spaces are expected to undergo frequent functional reconfigurations as pedagogical models, research programmes and organisational requirements evolve. For these areas, flexibility, adaptability and deconstructability are therefore more relevant design drivers than maximising the service life of specific finishes or partitions. The ability to reconfigure layouts, dismantle internal components without damage and reuse or recycle them is a key condition for long-term functional resilience, but it requires a different type of indicator than the one developed here.

By contrast, envelope components—façades, roofs and external shading systems—are long-lived, capital-intensive systems whose replacement events have a disproportionate impact on costs, disruption to users and environmental burdens. Their performance is also closely tied to the NZEB and ITACA/CAM objectives described in Chapter 3, particularly in relation to thermal performance, airtightness, solar control and protection of the structure and interiors. For these reasons, the envelope is treated as the main "durability-critical" subsystem in the DRH case study.

Consequently, the indicator developed in this chapter quantifies, for each envelope component family, the expected number of replacements over a 50-year reference period, while interior elements are discussed qualitatively in terms of adaptability and ease of disassembly. This selective focus allows the analysis to remain consistent with the overall sustainability framework of DRH, while concentrating effort on those components whose replacement cycles are most relevant for long-term environmental and economic performance.

6.3 Implementation of DR on the DRH Case Study and Results

6.3.1 Data sources and identification of envelope components

The implementation of the Durability Ratio (DR) indicator for the Digital Revolution House (DRH) builds directly on the existing energy model prepared for the Italian building regulation "Legge 10". The main technical document used is the report:

000131_001_ESE_IME_RSP_001_00 rel legge 10_rev1.pdf

Within this report, two sets of tables were particularly relevant:

- **"Involucro edilizio e ricambi d'aria"** – These tables list all envelope constructions used in the EDILCLIMA energy model, grouped into four series:
    - M-series (walls, "Muro / Muratura"),
    - P-series (floors, "Pavimento"),
    - S-series (roofs and ceilings, "Solaio / Soffitto"),
    - W-series (windows and glazed components, "Serramento").
- **"Dettaglio del fabbisogno di potenza dei locali"** – For each thermal zone and each room ("locale"), lists every envelope element with:
    - construction code (M1, M2, …, P1, …, S1, …, W1, …),
    - description,
    - orientation/exposure,
    - and surface area Sup. [m²].

These tables provide a complete and consistent basis for identifying all envelope components and their areas, which are required for the DR calculation.

Definition and description of thermal zones

In the EDILCLIMA model the DRH is subdivided into six thermal zones, primarily according to floor level, exposure and HVAC set-points. For the purpose of the durability assessment, these zones are interpreted as follows:

- **Zone 1 – Basement technical level (Piano interrato)**

Includes underground technical rooms, plant rooms, storage and service spaces, plus the basement circulation and stair cores (Locales 51–56 in the Legge 10 tables). The envelope considered here consists mainly of retaining walls against soil (M6), walls to technical rooms (M5), floor on igloo system (P4), external soffit (S4) and basement courtyard windows (W5).

- **Zone 2 – Ground floor: Atrium and laboratories (Piano terra)**

Includes the main public atrium, ground-floor laboratory rooms, a break / refreshment area, corridors and staircases (Locales 1–9). The relevant envelope elements are the ventilated external wall (M2), spandrel panels (M3), radiant floor over garage/technical room (P2), soffit over loggia (S3) and ground-floor windows (W4).

- **Zone 3 – First floor: teaching laboratories and study areas (Piano primo)**

Includes teaching laboratories, macro research environments / open-plan study areas, distribution corridors and staircases (Locales 11–18). The envelope is mainly composed of external walls with lamellas (M1), spandrel panels (M3), wall facing loggia (M4), loggia glazing (W2/W3) and soffit over loggia (S3).

- **Zone 4 – Second Floor: laboratories and study areas (Piano secondo)**

Functionally like Zone 3, with laboratories, open-plan research rooms, corridors and stair cores (Locales 21–28). The same family of envelope components appears again: M1, M2, M3, M4, P1 (floor over loggia) and W1/W2/W3 windows.

- **Zone 5 – Third Floor: laboratories and seminar rooms (Piano terzo)**

Includes laboratories, seminar / meeting rooms, corridors and stair cores (Locales 31–38). Again, dominated by M1 external walls, M3 spandrels, M4 loggia walls, P1 floors over loggia and W1–W3 windows.

- **Zone 6 – Fourth Floor: upper laboratories and roof-adjacent spaces (Piano quarto)**

Includes: the top regular floor with laboratories and circulation (Locales 41–48). In addition to M1/M2/M3/M4, this zone also interfaces with the main roof (S1) and ceiling over technical room (S2) in some spaces, plus the upper rows of façade windows (W1).

- **Zone 7 – Fifth Floor / Roof Level (Piano quinto)**

uppermost plant areas and stair head, mainly exposed through the stair tower roof slab (S5) and sandwich wall panels of the stairwell (M7).

Figure 22. Interior view of Zone 3 (first floor): open-plan teaching laboratory / study area with modular workstations and continuous façade glazing (W1–W3) providing daylight and visual connection to the exterior.

Figure 21. Interior view of Zone 3 distribution corridor: linear access spine serving teaching laboratories and study rooms, with acoustic ceiling treatment and clearly legible wayfinding (sector 1A).

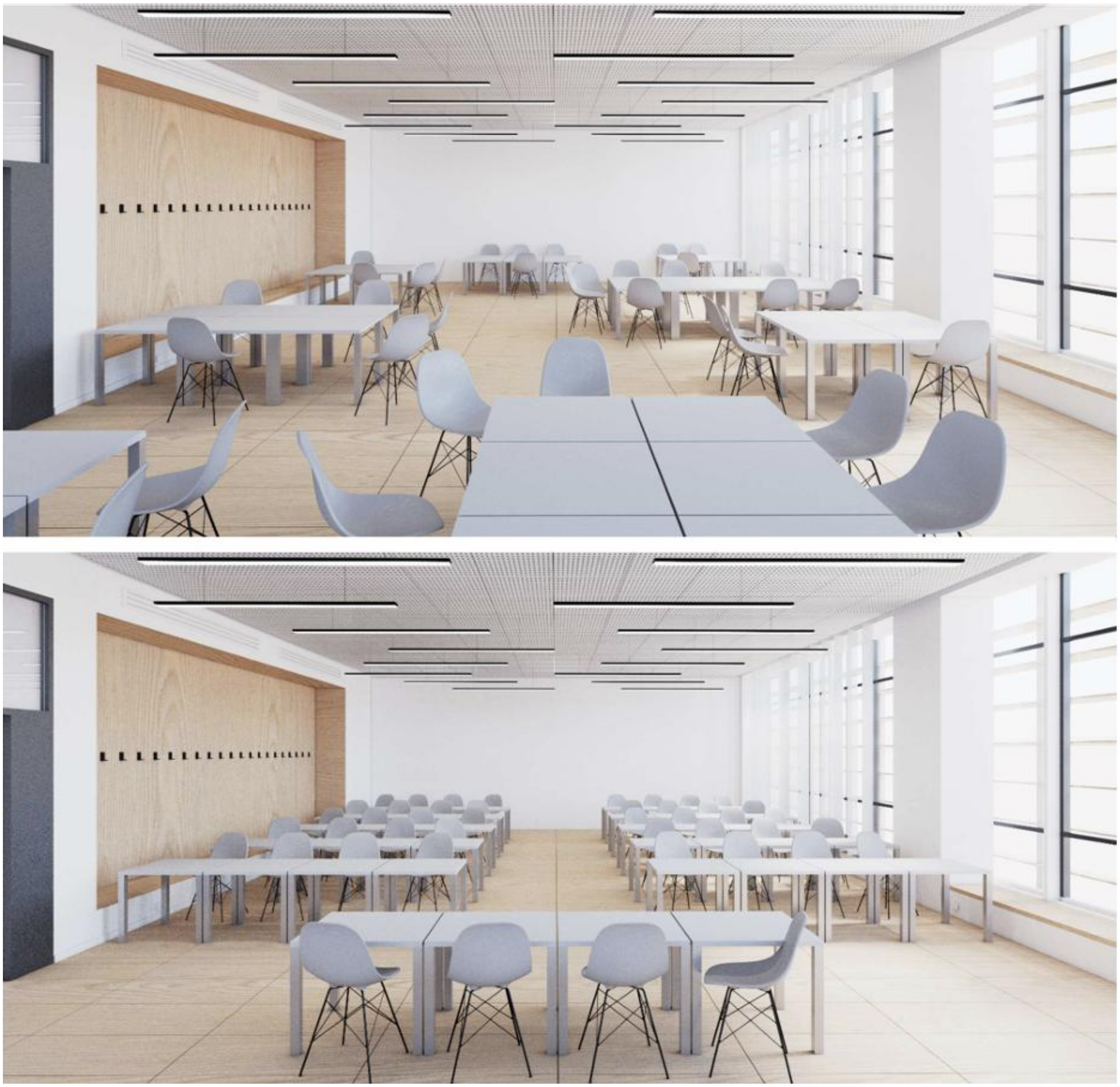


Figure 23. Interior views of Zone 5 (third floor) seminar / meeting room: flexible learning space with movable tables and chairs, shown in low-density study configuration (top) and high-density seminar configuration (bottom) along the glazed façade (W1–W3).

Component families considered in the durability analysis

The Legge 10 report distinguishes a series of construction types through alphanumeric codes. For the durability indicator, the analysis focuses on the following envelope component families:

Table 26. Wall components (M-series)

Code	Component name (EN [IT])	Main exposure / location	Zones where used	Layer build-up inside → outside (EN [IT])
M1	External wall with slats [Parete esterna con lamelle]	Perimeter façade of upper research levels, with external lamella cladding; walls between heated spaces and external air.	Zones 3–6 (1st–4th floor)	1. Internal surface resistance 2. Gypsum plasterboard [Cartongesso in lastre] 3. Unventilated cavity [Intercapedine non ventilata] 4. Generic structural concrete layer [C.I.S. in genere] 5. Rock-wool insulation panel [Pannello in lana di roccia] 6. ETICS plastic render [Intonaco plastico per cappotto] 7. External surface resistance.
M2	Ventilated external wall [Parete esterna ventilata]	Perimeter façade with ventilated aluminium cladding; walls between heated spaces and external air, typically on ground floor and upper floors.	Zones 2–6	Same inner side as M1 (1–4) then: 5. Rock-wool insulation panel [Pannello in lana di roccia] 6. Strongly ventilated cavity [Intercapedine fortemente ventilata] 7. Aluminium cladding panels [Pannelli in alluminio].
M3	Spandrel / belt wall [Marcapiano]	Opaque belt under/over glazed façade zones and loggia glazing; between heated space and external air.	Zones 2–6	1. Gypsum plasterboard [Cartongesso in lastre] 2. Double-density rock-wool panels [Pannello in lana di roccia a doppia densità] 3. Second plasterboard layer [Cartongesso in lastre] 4. Rock-wool insulation [Lana di roccia] 5. Slightly ventilated cavity [Intercapedine debolmente ventilata] 6. Aluminium sheet [Alluminio].
M4	Wall towards loggia [Muro su loggia]	Perimeter walls facing the recessed loggias; between heated space and loggia (unconditioned).	Zones 3–6	1. Internal plasterboard [Cartongesso in lastre] 2. Non-ventilated cavity [Intercapedine non ventilata] 3. Semi-solid masonry block [Blocco semipieno] 4. Rock-wool insulation [Pannello in lana di roccia] 5. Strongly ventilated cavity [Intercapedine fortemente ventilata] 6. Aluminium cladding panels [Pannelli in alluminio].
M5	Wall towards technical room [Muro su locale tecnico]	Internal-external separating wall between heated spaces and technical rooms / plant areas in the basement.	Zone 1 (basement)	1. Internal gypsum plaster [Intonaco di gesso] 2. Expanded-clay concrete layer [C.A. di argilla espansa – C.I.S. di argilla espansa] 3. Rigid mineral-fibre board [Fibre minerali felspatiche – pannello rigido] 4. Expanded-clay concrete layer [C.I.S. di argilla espansa].
M6	Retaining wall against ground / tank [Muro su vasca controterra]	Basement wall in contact with soil and underground tank; between heated space and ground.	Zone 1 (basement)	1. Internal gypsum plaster [Intonaco di gesso con inerti] 2. Expanded-clay concrete [C.I.S. di argilla espansa] 3. Rigid mineral-fibre board [Fibre minerali – pannello rigido] 4. Generic concrete / structural wall [C.I.S. in genere / calcestruzzo].
M7	Stairwell wall at roof level [Parete scala)	External envelope of the stair tower emerging on the roof;	Zone7 (roof	1. Inner steel sheet [Lamiera d'acciaio] 2. Factory-bonded polyurethane foam [Poliuretano espanso in

Code	Component name (EN [IT])	Main exposure / location	Zones where used	Layer build-up inside → outside (EN [IT])
	in copertura]	between stairwell and external air.	stair volume)	fabbrica] 3. Outer steel sheet [Lamiera d'acciaio]. Sandwich metal panel (steel + PUR insulation).

Table 27. Floor components (P-series)

Code	Component name (EN [IT])	Main exposure / location	Typical zones	Layer build-up inside → outside (EN [IT])
P1	Floor over loggia [Pavimento su loggia]	Floor slab above recessed loggias, separating heated interior from unconditioned loggia below.	Upper levels with loggias (Zones 3–6)	1. Internal floor finish (plastic / tiles) [Rivestimento plastico di pavimento] 2. Unventilated cavity / service void [Intercapedine non ventilata] 3. Gravel/sand concrete slab [Soletta in calcestruzzo con ghiaia e sabbia] 4. Mineral-fibre insulation [Isolante in fibra minerale] 5. Exterior plaster / soffit finish [Intonaco esterno].
P2	Radiant floor over technical room / garage [Pavimento radiante su locale tecnico/garage]	Ground-floor and upper floors where a radiant heating system is installed above unconditioned technical rooms or garages.	Mainly Zone 2 and some laboratory zones	1. Ceramic tiles [Piastrelle in ceramica] 2. Screed with embedded radiant pipes [Massetto con impianto radiante] 3. XPS insulation [Pannello in XPS] 4. Structural concrete slab [Solaio in calcestruzzo].
P3	Floor over technical room / garage (non-radiant) [Pavimento su locale tecnico/garage]	Similar situation as P2 but without radiant system (circulation, some service areas).	Zones 2 and 5–6 where specified	1. Floor finish (tiles / screed) [Rivestimento di pavimento] 2. Lean concrete [Magrone in calcestruzzo] 3. Polyethylene vapour barrier [Foglio in polietilene] 4. EPS insulation [Isolante in EPS] 5. Structural concrete slab [Solaio in calcestruzzo].
P4	Laboratory floor over igloo system [Pavimento laboratorio su igloo]	Basement and ground-floor laboratories over ventilated crawl-space ("igloo") systems to control moisture and radon.	Primarily Zone 1 (basement labs)	1. Laboratory floor finish [Rivestimento di laboratorio] 2. Screed [Massetto] 3. Structural slab over plastic "igloo" void formers [Solaio su casseri a perdere tipo igloo] 4. Ventilated crawl space [Vespaio aerato].

Table 28. Roof and ceiling components (S-series)

Code	Component name (EN [IT])	Main exposure / location	Typical zones	Layer build-up inside → outside (EN [IT])
S1	Main roof slab [Copertura]	Horizontal roof above the fourth floor; between upper laboratories and external air.	Zone 6 roof	(From stratigraphy sheet) Typical: 1. Internal plaster / ceiling finish [Intonaco interno] 2. Structural concrete slab [Solaio in calcestruzzo] 3. Thermal insulation (e.g. XPS / mineral wool) [Isolante termico] 4. Waterproofing membrane [Guaina impermeabile] 5. External protection layer / screed [Massetto di pendenza / finitura].
S2	Ceiling to technical room	Interior soffit separating heated space from	Zones with plant rooms	1. Internal plasterboard ceiling [Controsoffitto in cartongesso] 2. Structural slab [Solaio in calcestruzzo] 3. Possible insulation

Code	Component name (EN [IT])	Main exposure / location	Typical zones	Layer build-up inside → outside (EN [IT])
	[Soffitto su locale tecnico]	technical room below.	below (Zones 4–6)	layer towards technical room [Isolante termico] 4. Technical room finish.
S3	Ceiling over loggia [Soffitto su loggia]	Soffit of heated spaces over unconditioned loggias.	Zones 2–5 where loggias exist	1. Internal plaster / ceiling finish [Intonaco interno] 2. Structural slab [Solaio in calcestruzzo] 3. External plaster towards loggia [Intonaco verso loggia].
S4	Ceiling over exterior [Soffitto su esterno]	Soffit of slabs projecting to the exterior (e.g. canopies, underpasses).	Mainly Zone 1 and 2	1. Internal finish [Intonaco interno] 2. Structural concrete slab [Solaio in calcestruzzo] 3. External plaster / protective coating [Intonaco esterno / rivestimento].
S5	Stair tower roof slab [Tetto scala piano in copertura]	Flat roof slab of the stair tower, directly exposed to weather.	Roof stair volume Zone 7	1. Internal plaster [Intonaco interno] 2. Structural concrete slab [Solaio in calcestruzzo] 3. Insulation [Isolante termico] 4. Waterproofing membrane [Guaina impermeabile] 5. External finish (gravel / tiles) [Strato di protezione esterno].

Table 29. Window components (W-series)

Code	Component name (EN [IT])	Main exposure / location	Typical zones	Generic build-up
W1	Façade window [Serramento facciata]	Main curtain-wall / ribbon windows on teaching and research façades.	Zones 2–6	Thermally broken aluminium frame [Telaio in alluminio a taglio termico] + double/low-E glazing unit [Vetrocamera basso-emissivo].
W2	Loggia glazing [Vetrata loggia]	Glazed elements closing recessed loggias.	Zones 3–5	Similar to W1, adjusted to loggia geometry.
W3	Loggia lateral window [Laterale loggia]	Narrow side windows to loggias.	Zones 3–5	As W2; smaller modules.
W4	PT glazing [Vetrata PT]	Larger ground-floor glazing to atrium and public areas.	Zone 2	Aluminium / steel framed curtain wall with double glazing.
W5	Internal court window [Serramento cortile interrato]	Windows towards the underground courtyard at basement level.	Zone 1	Aluminium frame + double glazing, in contact with semi-underground external air.

Linear thermal bridges (Z-series) and purely internal partitions are excluded from the durability calculation because the proposed indicator targets the external envelope and the interfaces with unconditioned spaces, where replacement cycles have the strongest implications in terms of embodied impacts, maintenance and disruption of use.

6.3.2 Determination of envelope areas

The first step in applying the durability indicator to the Digital Revolution House is to establish a consistent geometric basis for all subsequent calculations. For this purpose, the envelope areas associated with each Legge 10 construction type (M-, P-, S- and W-series) were quantified in a two-stage process, starting from the thermal-zone data provided by the EDILCLIMA energy model and then aggregating these values to building level.

Stage 1 – Areas by component and thermal zone

The geometric information was extracted from the "Potenze di progetto dei locali" tables of the Legge 10 documentation, which provide, for every thermal zone and for each room within that zone, the envelope elements participating in the heat balance. Each element is referenced by its internal code (e.g. M1, M2, P2, S3, W1) and associated with an exchange area Sup.[m²]. As a preliminary step, the list of codes appearing in these schedules was cross-checked against the summary tables of opaque and transparent components ("Caratteristiche termiche dei componenti opachi dell'involucro edilizio" and "Caratteristiche termiche dei componenti finestrati") in order to confirm the set of envelope typologies to be considered in the durability assessment.

For each component code $i$and each thermal zone z, all occurrences of that code in the rooms belonging to zone $z$were identified and the corresponding areas were summed, yielding a zone-specific area $A_{i,z}$:

$$A_{i,z}\ [\text{m}^2] = \sum_{k \in \text{rooms of zone } z} \text{Sup}_{i,k}$$

Only those constructions that separate conditioned spaces from external air, semi-external spaces (loggias), ground or underground volumes, or unconditioned technical rooms/garages were retained, in line with the Legge 10 definition of the thermal envelope. Internal partitions between heated spaces were excluded, as they do not contribute to the external or semi-external boundary of the building and are therefore not relevant for the envelope durability indicator. The resulting matrix of $A_{i,z}$ values, reported in the first table, provides a detailed picture of how each construction type is distributed across the different zones of the building.

Stage 2 – Aggregation to building level

In a second stage, these zone-wise areas were aggregated over all zones in order to obtain a single building-level area for each construction type i:

$$A_i \ [\text{m}^2] = \sum_{z=1}^{n_z} \quad A_{i,z}$$

Table 30. Areas per envelope component and zone (Legge 10 model)

Zone	Code	Component name (EN [IT])	Area (A_{i,z}) [m²]
1	M5	Wall to technical room [Muro su locale tecnico]	681.60
1	M6	Retaining wall against ground [Muro su vasca controterra]	136.16
1	P4	Laboratory floor over igloo [Pavimento laboratorio su igloo]	1 046.00
1	S4	Ceiling over exterior [Soffitto su esterno]	390.00
1	W5	Courtyard window [Serramento cortile interrato]	390.00
2	M2	Ventilated external wall [Parete esterna ventilata]	303.28
2	M3	Spandrel / belt wall [Marcapiano]	162.78
2	P2	Radiant floor over technical room/garage [Pavimento radiante su locale tecnico/garage]	608.00

Zone	Code	Component name (EN [IT])	Area (A_{i,z}) [m²]
2	P3	Floor over technical room/garage (non-radiant) [Pavimento su locale tecnico/garage]	192.00
2	S3	Ceiling over loggia [Soffitto su loggia]	29.46
2	W4	Ground-floor glazing [Vetrata PT]	543.75
2	W1	Façade window [Serramento facciata]	18.85
3	M1	External wall with slats [Parete esterna con lamelle]	175.12
3	M2	Ventilated external wall [Parete esterna ventilata]	153.05
3	M3	Spandrel / belt wall [Marcapiano]	166.22
3	M4	Wall on loggia [Muro su loggia]	69.28
3	P2	Radiant floor over technical room/garage [Pavimento radiante su locale tecnico/garage]	50.00
3	S3	Ceiling over loggia [Soffitto su loggia]	29.46
3	W1	Façade window [Serramento facciata]	389.06
3	W2	Loggia glazing [Vetrata loggia]	19.80
3	W3	Loggia lateral window [Laterale loggia]	15.84
4	M1	External wall with slats [Parete esterna con lamelle]	109.56
4	M2	Ventilated external wall [Parete esterna ventilata]	21.66
4	M3	Spandrel / belt wall [Marcapiano]	247.80
4	M4	Wall on loggia [Muro su loggia]	87.16
4	P1	Floor over loggia [Pavimento su loggia]	29.43
4	S3	Ceiling over loggia [Soffitto su loggia]	29.40
4	W1	Façade window [Serramento facciata]	317.60
4	W2	Loggia glazing [Vetrata loggia]	19.80

Zone	Code	Component name (EN [IT])	Area (A_{i,z}) [m²]
4	W3	Loggia lateral window [Laterale loggia]	15.84
5	M1	External wall with slats [Parete esterna con lamelle]	197.12
5	M2	Ventilated external wall [Parete esterna ventilata]	28.88
5	M3	Spandrel / belt wall [Marcapiano]	168.35
5	M4	Wall on loggia [Muro su loggia]	108.37
5	P1	Floor over loggia [Pavimento su loggia]	14.73
5	S3	Ceiling over loggia [Soffitto su loggia]	14.73
5	W1	Façade window [Serramento facciata]	385.09
5	W3	Loggia lateral window [Laterale loggia]	31.68
7	M7	Stairwell wall at roof level [Parete scala]	64.00
7	S5	Stair tower roof slab [Tetto scala piano in copertura]	66.00

Table 31. Total area per component code (building level, Legge 10 envelope)

Code	Component name (EN [IT])	Total area (A_i) [m²]
M1	External wall with slats [Parete esterna con lamelle]	481.80
M2	Ventilated external wall [Parete esterna ventilata]	506.87
M3	Spandrel / belt wall [Marcapiano]	745.15
M4	Wall towards loggia [Muro su loggia]	264.81
M5	Wall to technical room [Muro su locale tecnico]	681.60
M6	Retaining wall against ground [Muro su vasca controterra]	136.16
M7	Stairwell wall at roof level [Parete scala in copertura]	64.00
P1	Floor over loggia [Pavimento su loggia]	44.16

Code	Component name (EN [IT])	Total area (A_i) [m²]
P2	Radiant floor over technical room/garage [Pavimento radiante su locale tecnico/garage]	658.00
P3	Floor over technical room/garage (non-radiant) [Pavimento su locale tecnico/garage]	192.00
P4	Laboratory floor over igloo system [Pavimento laboratorio su igloo]	1 046.00
S1	Main roof [Copertura]	890.50
S2	Ceiling to technical room [Soffitto su locale tecnico]	459.00
S3	Ceiling over loggia [Soffitto su loggia]	103.05
S4	Ceiling over exterior [Soffitto su esterno]	390.00
S5	Stair tower roof slab [Tetto scala piano in copertura]	66.00
W1	Façade window [Serramento facciata]	1 110.60
W2	Loggia glazing [Vetrata loggia]	39.60
W3	Loggia lateral window [Laterale loggia]	63.36
W4	Ground-floor glazing [Vetrata PT]	543.75
W5	Courtyard window [Serramento cortile interrato]	390.00

The set of $A_i$values represent the total exchange surface of each M-, P-, S- and W-series component in the DRH envelope and is reported in Table 25, together with the component descriptions. The overall envelope area is then obtained as:

$$A_{\text{total}}\,[\text{m}^2] = \sum_i A_i = 8876.41\,\text{m}^2$$

This total envelope area A_{total}forms the denominator of the building-level Durability Ratio, while the individual $A_i$values act as weighting factors when combining the replacement cycles of different components into a single indicator.

6.3.3 Assignment of service life and component-level DR

For each envelope component family, a governing layer was identified from a durability perspective (e.g. ETICS system, roof waterproofing, window unit), and a reference service life $SL_i$was assigned based on:

- the ISO 15686 service-life planning framework.
- typical reference service lives reported in product category rules and environmental product declarations (EPDs).
- technical guidance from manufacturers and professional bodies; and
- where relevant, the protected or exposed condition of the component in the DRH configuration.

The number of full replacement cycles over the 50-year reference period was then computed as:

$$N_{\text{rep},i} = \lfloor \frac{50}{SL_i} \rfloor$$

component-level Durability Ratio was defined as:

$$DR_i = N_{\text{rep},i}$$

And a component-level contribution to the building DR:

$$\text{Contribution}_i = w_i \cdot N_{\text{rep},i}$$

Table 32. Component-level service lives and area-weighted contributions to the Durability & Replacement Cycles index for opaque wall elements of the DRH envelope.

Code	Component	Governing system (for SL)	Chosen SL_i(years)	Sources for the service life (short)	$N_{rep,i}$ = $\lfloor 50/SL_i \rfloor$	Contribution$_i$	DR $_i$ (component-level))
M1	External wall with ETICS (render on insulation on RC)	ETICS render + insulation	25	ETAG 004 (EOTA, 2013); ITB (2023) SOLTHERM HD ETICS EPD	50/25	0.109	2
M2	Ventilated external wall (RC + rock wool + Al panels)	Ventilated aluminium façade (cladding system)	50	Kalzip (2019) aluminium FC façade EPD; Etex (2018) EQUITONE EPD	50/50	0.057	1
M3	Spandrel / belt panel (PB + rock wool + Al sheet)	Light façade / insulated panel with Al sheet	40	PPA-Europe (2017) PU sandwich panel EPD	50/40	0.084	1
M4	Wall towards loggia (masonry + insulation + Al cladding)	Ventilated aluminium cladding over masonry	50	CCP (2023) Greenbloc EPD; CarbiCrete (2023) EPD; UL PCR for concrete masonry	50/50	0.030	1
M5	Wall to technical room (expanded-clay concrete + board)	Massive internal wall (semi-protected)	75	CCP (2023) Greenbloc EPD; CarbiCrete (2023) EPD; UL PCR for concrete masonry	50/75	0	0
M6	Retaining wall (expanded clay + concrete against soil)	Massive retaining concrete wall	75	CCP (2023) Greenbloc EPD; CarbiCrete (2023) EPD; UL PCR for concrete masonry	50/75	0	0
M7	Stairwell wall at roof (steel–PU–steel sandwich panel)	PU sandwich façade panel	50	PPA-Europe (2017) PU sandwich panel EPD	50/50	0.007	1

Table 33. Component-level service lives and area-weighted contributions to the Durability & Replacement Cycles index for floor elements of the DRH envelope.

Code	Component	Governing system (for SL)	Chosen SL_i(years)	Sources for the service life (short)	$N_{rep,i}$ = $\lfloor 50/SL_i \rfloor$	Contribution$_i$	DR $_i$ (component-level))
P1	Floor over loggia (Pavimento su loggia)	Concrete slab + external insulation + waterproofed/loggia build-up	50	Structural concrete floors and external thermal insulation systems are normally designed for ≥50 years; ceramic or similar finishes have documented RSL 50–75 years in EPDs, so 50 years is a conservative building-level value.	50/50	0.005	1

Code	Component	Governing system (for SL)	Chosen SL_i(years)	Sources for the service life (short)	$N_{rep,i}$ = ⌊50/SLi⌋	$Contribution_i$	DR_i (component-level))
P2	Radiant floor over technical room / garage (Pavimento radiante su locale tecnico/garage)	Concrete slab + XPS insulation + embedded radiant pipes	50	XPS/EPS insulation EPDs commonly use RSL = 50 years; hydronic underfloor heating pipes are typically designed for ≥50 years according to manufacturer data; the structural slab also has ≥50-year life.	50/50	0.074	1
P3	Floor over technical room / garage (non-radiant) (Pavimento su locale tecnico/garage)	Concrete slab + EPS insulation + screed	50	No embedded services, so the limiting elements are again the structural slab and insulation. EPS insulation technical documents and EPDs generally assume 50-year RSL; slabs are ≥50 years, so SL_i = 50 years is consistent.	50/50	0.022	1
P4	Laboratory floor over igloo system (Pavimento laboratorio su igloo)	Structural slab + ventilated void (igloo) + insulation + wearing surface	50	The igloo system is a permanent formwork for the slab; the structural and insulation layers are comparable to P3. As long as moisture is managed, a 50-year RSL is aligned with standard assumptions for such systems.	50/50	0.118	1

Table 34. Component-level service lives and area-weighted contributions to the Durability & Replacement Cycles index for roof and ceiling elements of the DRH envelope.

Code	Component	Governing system (for SL)	Chosen SL_i(years)	Sources for the service life (short)	$N_{rep,i}$ = ⌊50/SLi⌋	$Contribution_i$	DR_i (component-level))
S1	Main warm flat roof over top floor (Copertura)	Roof waterproofing system (bituminous / single-ply membrane + insulation)	30	EPDs for flexible bitumen roof sheets typically assume an RSL of 30 years for the initial waterproofing, with possible renewals. Structural concrete roof slabs are designed for ~50 years, so the membrane governs replacement.	50/30	0.1	1
S2	Ceiling below roof / technical room (Soffitto su locale tecnico)	Suspended gypsum-board ceiling / plastered soffit	30	Gypsum-board/suspended-ceiling EPDs and ISO 15686-based studies usually declare an RSL of about 30 years for ceiling panels.	50/30	0.052	1
S3	Ceiling over loggia (Soffitto	Interior ceiling finish (gypsum/plaster)	30	Same material system as S2, with somewhat higher thermal stress;	50/30	0.012	1

Code	Component	Governing system (for SL)	Chosen SL_i(years)	Sources for the service life (short)	$N_{rep,i}$ = ⌈50/SL_i⌉	$Contribution_i$	DR_i (component-level))
	su loggia)	similar to S2		durability is still governed by gypsum/plaster finish and maintenance, so 30 years is a reasonable RSL.			
S4	Ceiling over exterior (Soffitto su esterno)	Exterior-facing soffit finish (exposed plaster/paint or boards)	30	Exposed soffits typically have replacement cycles governed by cladding/coating systems (25–40 years). A 30-year RSL is consistent with façade/soffit cladding life assumptions.	50/30	0.044	1
S5	Stair tower roof slab (Tetto scala piano in copertura)	Roof waterproofing package (as S1, smaller area)	30	Construction analogous to S1; roof membranes widely use 30-year RSL in EPDs. The structural slab is ≥50 years, so waterproofing governs.	50/30	0.007	1

Table 35. Component-level service lives and area-weighted contributions to the Durability & Replacement Cycles index for window and glazing elements of the DRH envelope.

Code	Component	Governing system (for SL)	Chosen SL_i(years)	Sources for the service life (short)	$N_{rep,i}$ = ⌈50/SL_i⌉	$Contribution_i$	DR_i (component-level))
W1	Main façade windows (Serramento facciata)	Standard façade windows; BBSR guidelines and several window EPDs adopt a 40-year RSL for window units.	40	ISO 15686-8; BBSR (2017) service-life table for windows (~40 years); representative EU window EPDs adopting 40-year RSL.	50/40	0.125	1
W2	Loggia front glazing (Vetrata loggia)	Same insulated-glazing-unit (IGU) + frame technology as W1, with more sheltered exposure; using 40 years is conservative and consistent.	40	Same system as W1; 40-year RSL as per BBSR window data and associated window/roof-window EPDs.	50/40	0.004	1
W3	Loggia side glazing (Laterale loggia)	Side panels made with the same window system as W1–W2; therefore the same RSL applies.	40	Identical window system to W1–W2; 40-year RSL based on BBSR window values and window EPDs.	50/40	0.007	1
W4	Ground-floor large glazing (Vetrata PT)	Larger IGU or curtain-wall-like elements; most curtain wall/window EPDs assume 30–40 years and refer to BBSR; adopting 40 years maintains consistency.	40	Curtain-wall-like glazing; 40-year RSL consistent with BBSR data for windows/façade openings and curtain-wall/window EPDs.	50/40	0.061	1
W5	Courtyard glazing (Serramento cortile interrato)	Functionally equivalent to other windows; exposure differs slightly, but durability is still governed by IGU + frame.	40	Same IGU + frame technology as other windows; 40-year RSL supported by BBSR window table and European window EPDs.	50/40	0.044	1

Results of the Durability & Replacement Cycles calculation

The summary table reports, for each envelope component, its reference service life SL_i, the resulting number of full replacements over the 50-year reference period $N_{rep,i} = \lfloor 50/SL_i \rfloor$, the area share $w_i = A_i/A_{env}$, and the corresponding area-weighted contribution $Contribution_i = w_i \cdot N_{rep,i}$ to the building-level durability index. Components with longer service lives (e.g. massive internal and retaining walls M5–M6 with $SL_i =$ 75 years and $N_{rep,i} = 0$) do not contribute to the replacement intensity, while components with shorter or equal service lives and large areas (e.g. the external walls with ETICS, the main roof, the laboratory floor, and the main façade windows) show the highest contributions.

The building-level Durability & Replacement Cycles index is computed as the area-weighted average of the component-level replacement factors:

$$DR_{building} = \sum_{i=1}^{n} w_i \cdot N_{rep,i} = \sum_{i=1}^{n} \left(\frac{A_i}{A_{env}} \cdot N_{rep,i}\right)$$

Using the DRH envelope data ($A_{env} = 8876.41$ m²), the sum of the area-weighted contributions of all wall, floor, roof and window components gives:

$$DR_{building} \approx 0.96$$

This means that, on average, each square metre of the DRH envelope undergoes slightly less than one full replacement cycle in 50 years, indicating a relatively low replacement intensity.

According to the pilot scoring bands defined for this thesis, values of $DR_{building} \leq 1.0$ are classified as "very high durability" and correspond to the maximum SBTool/ITACA score. The DRH building therefore attains a Durability & Replacement Cycles score of +5 on the adopted −1…+5 scale.

6.4 Validation of Results and Robustness Check

Following the application of the indicator to the Digital Revolution House, a robustness check was performed to verify the quality of the results and the feasibility of the proposed method. The application confirmed that the indicator effectively bridges the gap between theoretical circularity goals and available campus data.

Verification of Data Workflow The pilot application demonstrated that the reliance on "Legge 10" regulatory energy reports is a robust strategy for campus assessments. The data extraction process proved that the necessary geometric inputs (surface areas of specific technological components) and typological descriptions (i.e., the type of component, such as a 'ventilated facade' or 'flat roof membrane') are consistently available in standard compliance documents.

It is important to note that for the DRH case study, the component areas were explicitly tabulated due to the requirements of the ITACA certification process. However, the method's validity is maintained for non-certified buildings because the essential data for calculating service life—the component type—can be reliably extracted from architectural plans and material specifications, even if the detailed stratigraphy layers are unavailable. The component type is sufficient to establish a Reference Service Life from international standards. This validates the initial hypothesis that a circularity assessment can be performed without generating new, resource-intensive digital twins, provided that basic technical archives are accessible. The workflow successfully transformed static compliance data into dynamic, service-life-oriented information.

Sensitivity of the Results The results obtained from the case study indicate sufficient sensitivity to distinguish between component families. The indicator successfully differentiated between long-life elements (such as massive internal walls or concrete retaining structures) and components with higher replacement frequencies (such as external finishing systems and glazed units). This granularity is essential for decision-making, as it allows facility managers to identify specific "hotspots" of material turnover within the building envelope rather than receiving a generic, flat score.

If the Result is **NOT Sensitive**	If the Result IS **Sensitive**
Score: One flat number.	Score: A breakdown by component type.
Action: Maybe everything needs to be replaced.	Action: Need to focus the circularity efforts on replacing External Finishing Systems with more durable materials, as they are driving down the building's overall score.
Outcome: Inefficient use of budget.	Outcome: Targeted, high-impact maintenance planning.

Limitations and Reliability While the calculation proved feasible, the robustness check highlighted a dependency on the quality of external reference service-life (RSL) databases. Since the indicator relies on theoretical RSL values (from standards or EPDs) rather than empirical maintenance records, the results represent a "design-potential" durability rather than a "performance-actual" durability. However, within the context of a protocol like SBTool/ITACA, which is often applied at the design or handover stage, this level of approximation is consistent with other predictive criteria (such as energy modelling).

The successful completion of the assessment on a complex, mixed-use building like the DRH validates the scalability of the approach. The method proved capable of handling diverse component types (from advanced curtain walls to standard basement structures) within a single aggregated index. This confirms that the indicator is robust enough to be rolled out across a wider portfolio of university assets with varying ages and construction types.

Chapter 7. Conclusion & Future Work

7.1 Key findings

This thesis set out to enrich the SBTool/ITACA framework for university campuses by introducing a circular-economy enhancement that is both evidence-based and operationally feasible in real campus settings. The overarching aim was to respond to the main research question: in what ways might SBTool/ITACA be improved for campuses to be made more sustainable through the incorporation of a clear CE criterion?

To address this question, a seven-step research flow was implemented, starting from a curated CircularB COST corpus and culminating in a tested indicator at the Politecnico di Torino campus. The workflow involved: (1) literature review and corpus screening; (2) hand-extraction of building-scale CE/sustainability indicators; (3) classification of these indicators with the CircularB COST framework; (4) cross-mapping to SBTool/ITACA; (5) selection and operationalisation of a single high-leverage gap indicator; (6) application to the Digital Revolution House (DRH) as case study; and (7) validation and refinement of the proposed indicator for protocol integration.

The analysis of the 15-paper corpus confirmed that current CE indicators for buildings are strongly skewed towards environmental aspects and energy–materials performance, with much weaker coverage of long-term use, maintenance and campus-specific decision contexts. When these indicators were mapped into the SBTool/ITACA slot structure (Area → Issue → Criterion), most could be positioned as Criterion–Exact or Criterion–Partial, especially within the energy and materials-management areas, while a smaller subset appeared as Category-Partial or Issue-Partial. This pattern showed that, although SBTool/ITACA already captures many mainstream performance constructs, it still lacks explicit, operational indicators for some circular-economy aspects, particularly those related to long-term durability and replacement cycles rather than one-off design choices.

Restricting the analysis to Category- and Issue-Partial items, a specific indicator on Durability and Replacement Cycles was identified within the Service Quality area (E2: Optimisation & Maintenance) as the most promising key gap: it links circularity to the long-term performance of the envelope through the lens of repair, refurbishment and "slow" material loops, while remaining compatible with SBTool/ITACA's structure and scoring logic. Building on this, the thesis formulated a Durability Ratio (DR) indicator defined over a 50-year reference period, consistent with the service-life horizon implicitly adopted in both SBTool/ITACA and in many EPD and standard references.

A central methodological contribution was the demonstration that the data required for this indicator can be derived from existing documentation, without imposing unrealistic information demands on campus projects. In particular, the Legge 10 documentation of the DRH, generated with EDILCLIMA, was used as the backbone of the computation. The "Potenze di progetto dei locali" tables, together with the summary sheets for opaque and transparent components, provided a consistent description of envelope elements by code (M-, P-, S-, W-series) and associated exchange areas. These tables were reorganised by thermal zone and construction type to obtain zone-wise areas $A_{(i,z)}$, and then aggregated to building level to derive a total surface A_i for each envelope construction, which serves as the area weight in the Durability Ratio.

Service-life values SL_i for each construction type were assigned based on EPDs, technical guidance and standardised RSL assumptions for ETICS, ventilated façades, sandwich panels, roofs, ceilings, floor build-ups and window systems. From these, the number of full replacement cycles over 50 years was computed as $N_{rep,i} = \lfloor 50/SL_i \rfloor$. At building level, the Durability Ratio was constructed as an area-weighted measure of replacement intensity over the 50-year horizon, combining the replacement cycles of each element with its share of the total envelope surface.

Applied to the DRH, the indicator showed that the campus building envelope presents a relatively balanced durability profile: long-life massive walls and retaining structures (with no expected full replacement within 50 years) coexist with shorter-lived systems such as ETICS façades and window/glazing families, which require one or two replacements in the same period. The resulting Durability Ratio for the DRH envelope is slightly below one replacement per square metre over 50 years, meaning that—on average—each square metre of the envelope undergoes just under one full replacement cycle in that horizon.

Taken together, these findings demonstrate that it is possible to (i) derive a protocol-ready durability indicator for campuses from the literature and CircularB COST framework, (ii) position it within the SBTool/ITACA structure without overlaps, and (iii) implement and interpret it in a real campus building using documentation that is already produced for regulatory purposes. In this way, the thesis offers a concrete answer to the research questions concerning CE gaps in SBTool/ITACA, the identification and placement of a key gap indicator, and the feasibility of testing it in a campus setting.

7.2 Contributions of the thesis

The contributions of this research can be grouped into three main strands: conceptual, methodological, and practical.

Conceptual contributions

Conceptually, the thesis connects three domains that are often treated separately: circular-economy indicator research (through the CircularB COST framework), building sustainability protocols (SBTool/ITACA), and campus-scale asset management. By systematically mapping literature-derived CE indicators to the SBTool/ITACA slot structure, it clarifies where current campus assessments are already aligned with circular principles and where they lack explicit, measurable criteria. The identification of Durability and Replacement Cycles as a Category-Partial gap within Service Quality makes visible the importance of long-term performance and maintenance planning in campus circularity, rather than focusing solely on upfront design measures.

The thesis also reframes durability and service life as circular issues. By linking the indicator explicitly to “slow” resource loops and to repair/refurbish strategies in the 10R hierarchy, the work underlines that avoiding premature replacement is a circular strategy in its own right, complementary to reuse and high-quality recycling. This conceptualisation is particularly meaningful for campuses, where asset life and maintenance strategies have direct budgetary and educational implications.

Methodological contributions

Methodologically, the thesis demonstrates a reproducible seven-step flow for indicator development and integration into an existing protocol. It shows how a curated research corpus can be transformed into a structured indicator set, coded through CircularB COST, and then cross-walked into SBTool/ITACA in a transparent way, with explicit documentation of Exact/Partial/Gap statuses. This is a transferable method that could be applied to other clusters of circular indicators and to other protocol families.

A second methodological contribution is the integration of regulatory energy documentation (Legge 10) with service-life data from EPDs and technical sources, via a fully Excel-based workflow. The work clarifies how envelope areas can be reconstructed by component code and zone, and how these areas can be re-used as weights in a durability indicator without re-modelling the building from scratch. This type of “document-driven” computation is particularly relevant for campuses, which often have extensive archives of design and compliance reports but limited resources for building full digital twins.

Practical contributions

Practically, the thesis delivers a ready-to-implement Durability Ratio indicator that can be integrated within the ITACA campus module as part of the Service Quality area. It specifies the scope (envelope constructions separating conditioned spaces from exterior, semi-external or unconditioned technical spaces), defines the computational steps (from SL_i and $N_{rep,i}$ to the building-level DR), and provides a worked-out application on a real campus building. The DRH case study demonstrates that the indicator can be calculated and interpreted using information that is routinely available and that the resulting values are meaningful for distinguishing between more and less durable envelope strategies.

For campus decision-makers, the indicator offers a concise metric that can be read alongside energy and environmental scores: a higher Durability Ratio signals a more replacement-intensive envelope over the reference period, with associated implications for material flows, embodied impacts and maintenance costs. In doing so, the thesis strengthens the capacity of SBTool/ITACA to act as a reference model for sustainability innovation in the university sector.

7.3 Limitations

The findings and contributions of this thesis must be interpreted in light of several limitations.

First, the indicator corpus used for the literature review was derived from a pre-filtered CircularB COST repository of 29 articles, of which 15 met the inclusion criteria for building-scale, indicator-based studies. While this ensures relevance and depth for each included paper, it also means that the mapping does not constitute an exhaustive survey of all CE indicators in the built-environment literature. Non-English studies, grey literature and sector-specific indicator sets (e.g., housing authorities, corporate campuses) may contain additional constructs that are not captured here.

Second, the cross-mapping between literature indicators and SBTool/ITACA inevitably involves judgement. Even with clear rules for assigning Exact, Partial or Gap status, the interpretation of whether a given indicator is "already represented" in SBTool or only partially addressed depends on how strictly one reads the intent, scope and thresholds of the protocol criteria. Different experts could arrive at slightly different mappings, especially for cross-cutting issues that straddle multiple Areas or Issues within SBTool/ITACA.

Third, the Durability Ratio itself is based on several simplifying assumptions. Service-life values were drawn from EPDs, technical guidelines and standardised RSL defaults, which, although widely used, may not fully capture climate-specific deterioration, construction quality, or campus-specific maintenance practices. The indicator works with integer numbers of full replacement cycles and does not account for partial replacements, minor repairs or performance degradation that does not trigger a full renewal. As a result, it offers a stylised representation of replacement intensity, not a detailed maintenance log.

Fourth, the application has been limited to a single, relatively recent NZEB campus building, the Digital Revolution House. The DRH benefits from contemporary design standards, high-performance envelope systems and detailed documentation. Older campus buildings, or those with incomplete documentation, may present very different patterns of durability and data availability. Moreover, the focus has been restricted to the envelope; the structural frame, internal finishes, technical services and outdoor spaces have not been assessed through the same durability lens, even though they may also play a key role in campus circularity.

Finally, the thesis has not attempted to couple the Durability Ratio directly with quantitative environmental or economic outcomes. Although it is clear that more frequent replacements imply higher material flows and embodied impacts, the indicator itself stops at the level of replacement counts per square metre. The integration with full LCA, LCC or portfolio-level asset management models remains outside the present scope.

These limitations do not undermine the validity of the results but indicate that the work should be seen as an initial, exploratory step towards more comprehensive circular-economy assessment on campus, rather than a definitive or universal solution.

7.4 Future Developments

At the protocol level, the Durability and Replacement Cycles indicator could be fully formalised and piloted within the ITACA campus module, including the definition of scoring scales, thresholds and documentation requirements. The same seven-step development logic used here could be extended to other Category- and Issue-level gaps identified in the cross-mapping—such as indicators related to adaptability, material passports or long-term resource planning—so that SBTool/ITACA progressively gains a more complete circular-economy profile. Alignment with Level(s) and with the ongoing CircularB KPI framework would help ensure coherence with European policy and facilitate broader uptake.

At the methodological level, the Durability Ratio should be applied to a broader sample of campus buildings with different ages, typologies and documentation quality. Comparing new constructions like DRH with older teaching blocks, laboratories or residences would provide insight into how replacement intensity varies across the campus portfolio and which envelope strategies are most robust over time. Incorporating BIM-based quantities and IFC models, where available, could reduce manual work, while still relying on the same core logic of area-weighted replacement cycles.

At the data and calibration level, future work could seek closer collaboration with facility-management units to access real maintenance records and replacement histories. Such empirical data would make it possible to calibrate or adjust the assumed service-life values, test the robustness of the indicator against observed behaviour, and refine the treatment of partial replacements, upgrades and refurbishment cycles. In time, this could lead to campus-specific service-life libraries that better reflect local climate, use patterns and maintenance cultures.

From a decision-making perspective, the Durability Ratio could be embedded into campus planning tools and scenario analyses. For example, alternative refurbishment options for an existing building could be compared not only in terms of energy and environmental scores but also in terms of how they shift the Durability Ratio over 50 years. Coupling the indicator with LCA and LCC would support integrated evaluations of “slow” circular strategies, helping campuses to prioritise interventions that combine reduced environmental burden with manageable maintenance and replacement costs.

Finally, there is scope to explore digital and automation opportunities. The Excel-based workflow demonstrated in this thesis offers transparency and accessibility, but future developments could involve semi-automated extraction of areas and construction codes from BIM models or Legge 10 files, as well as the deployment of campus-wide dashboards that track durability-related performance alongside existing SBTool/ITACA results. Such tools would resonate with the broader vision of campuses as “living laboratories,” where data-driven feedback loops help align day-to-day asset management with long-term circular-economy goals.

In conclusion, the thesis demonstrates that a targeted, campus-oriented circular indicator can be derived from the literature, anchored in an established protocol and made operational in a real building with existing data. While the work focuses on durability and replacement cycles as a first step, it opens a pathway for further enhancements, pointing towards a more circular and resilient future for university campuses.

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