Ref. Ares(2024)9190816 - 20/12/2024

D4.14 – Assessment of circularity for the developed solutions (1st version)

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DATE: 31 DEC 2024

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Technical References

Project Acronym	BIO4EEB
Project Title	BIO insulation materials for Enhancing the Energy performance of Buildings
Project Coordinator	3L
Project Duration	48 Months

Deliverable No.	D4.14
Dissemination level [1]	PU
Work Package	WP4
Task	Task 4.6
Lead Beneficiary	BYCN
Contributing Beneficiary(ies)	ABUD, EBC
Due date of deliverable	31 December 2024 (M24)
Actual submission date	20 December 2024

[1] PU – Public, fully open, e.g. web (Deliverables flagged as public will be automatically published in CORDIS project's page)
SEN – Sensitive, limited under the conditions of the grant agreement
Classified R-UE/EU-R – EU RESTRICTED under the commission Decision No2015/444
Classified C-UE/EU-C – EU CONFIDENTIAL under the commission Decision No2015/444
Classified S-UE/EU-S – EU SECRET under the commission Decision No2015/444

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Document history

V	Date	Author (Beneficiary)	Description
V0.1	05/11/2024	Jennifer PONTE (BYCN)	Table of Content (ToC)
V0.2	05/12/2024	Amina DACIC (ABUD), Evangelia TSIALA (EBC), Giorgia SIGNORETTO (EBC)	Chapter 3 and 4
V0.3	09/12/2024	Jennifer PONTE (BYCN)	First draft
V0.4	13/12/2024	Bruno LINEATTE (BYCN) Jennifer PONTE (BYCN) Amina DACIC (ABUD)	Version for reviewers
V0.5	20/12/2024	Jennifer PONTE (BYCN)	Final version - modifications made in accordance with reviewers' comments - Version with all comments visible for consideration in further work on T4.6
V1.0	20/12/2024	Jennifer PONTE (BYCN)	Final version - modifications made in accordance with reviewers' comments

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Executive Summary

This deliverable, part of the BIO4EEB project, provides an overview of the work carried out from June 2023 to December 2024 (M6 to M24) on the Task 4.6 ”Methodology for assessing circularity”. This task focuses on defining a certification process for assessing the circularity of products used in rehabilitation actions, and thereby covers the following main sub-objectives:

- Review circularity analysis in European projects, standardization activities and regulations,
- Identify the relevant parameters and KPIs for assessing circularity at material/component/building levels,
- Develop a circular referential analysis as an assessment tool,
- Assess the circular value of the BIO4EEB solutions and their contribution to the circularity value of each demosite,
- Develop a certification methodology regarding the characterization of circular material / products.

This report presents the methodology defined to achieve these objectives, structured into four main stages detailed in the document:

1. **Setting precise objectives and action plan**
2. **Literature review on circularity analysis**
3. **Development of a circular referential analysis**
4. **Development of a certification scheme**

The results of stages 1 to 3 are presented in this first version of the deliverable. The initial phase of setting objectives enabled to align the scope of the study with the broader goals of the BIO4EEB project and to ensure that all involved partners had a clear understanding of the input data requirements and expected outcomes. The literature review offered valuable insights into existing circularity indicators and methodologies used in European projects, standardization works, and scientific research, ensuring that the methodology is grounded in current best practices. The circular referential analysis stage provided a detailed selection of the most relevant parameters for assessing circularity.

These results constitute a solid basis for the final stage of the methodology consisting of developing the certification process, which will be included in the updated version of the deliverable at M48.

Through this structured methodology, the BIO4EEB project aims to advance the understanding and implementation of circularity in the construction industry, ultimately contributing to more sustainable building practices.

Disclaimer

Abbreviations and Acronyms

Abbreviation	Description
BIO4EEB	BIO Insulation materials for Enhancing the Energy performance of Buildings
C2C	Cradle to Cradle
CAT	Calculation and Assessment Tool
CI	Circularity indicator
CDW	Construction and demolition waste
CPR	Construction products regulation
DfD	Design for disassembly
DfD/A	Design for disassembly and adaptability
DoA	Description of the Action
ECM	Energy Conservation Measures
EMF	Ellen MacArthur Foundation
EPD	Environmental product declaration
EU	European Union
GHG	Greenhouse gas
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCA	Life cycle assessment
LCC	Life cycle costing
MCDA	Multi Criteria Decision Analysis
MCI	Material circularity indicator
PnP	Plug and Play
PRISMA	Systematic Reviews and Meta-Analyses
SLR	Systematic literature review
S-LCA	Social life cycle assessment
WP	Work Package

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1 Introduction

1.1 Purpose and target group

The final objective of Task 6 in WP4 is to define a certification process for assessing the circularity of the products introduced in the rehabilitation actions. At the end of the project, circularity indicators at product and building levels will be calculated and summarised to assess the circular value of the solutions developed by BIO4EEB.

This report provides an overview of the work carried out from June 2023 to December 2024 (M6 to M24). More precisely, this deliverable presents the methodology defined by the Task 4.6 partners to assess circularity in products and buildings, based on 4 steps described and detailed in the document. The results achieved in the first 3 stages (setting precise objectives and action plan, literature review on circularity analysis, development of a circular referential analysis) are presented and will provide the basis for the work carried out in stage 4 in the next months, which corresponds to developing the certification process.

The target group of this report is the consortium of the BIO4EEB project.

1.2 Contributions of partners

This report compiles contributions from EBC, ABUD and BYCN.

1.3 Relation to other activities

Given the consideration of the entire life cycle in the circular approach, there are important links with task 4.5 (Life Cycle Assessment for each developed solution components). In addition, with the aim of applying the certification scheme to the project's BIO4EEB solutions and demonstrators, WP3 activities (Development of new bio-based insulation materials and material combinations for enhanced insulation performance) will be linked to task 4.6, as well as task 4.2 (Demonstration in real demo-cases).

Finally, the results in terms of circularity assessment will be taken up and used in the BIO4EEB platform, task 4.6 is therefore linked to task 3.7 (Development of the BIO4EEB platform) and 4.7 (Demonstration and validation of the BIO4EEB platform).

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2 Methodology

Given the complexity and systemic dimension of analysing circularity in products and buildings, the partners involved in task 4.6 met very early in the project (M5) to agree on the methodology to be deployed to achieve the task's objectives.

The general methodology adopted can be summarised in the 4 main stages presented below:

- **Stage 1: Setting precise objectives and action plan**

This first stage consists in defining with all the partners involved the scope, the entry data and the outcomes of the task. The objectives were defined and the process established step by step.

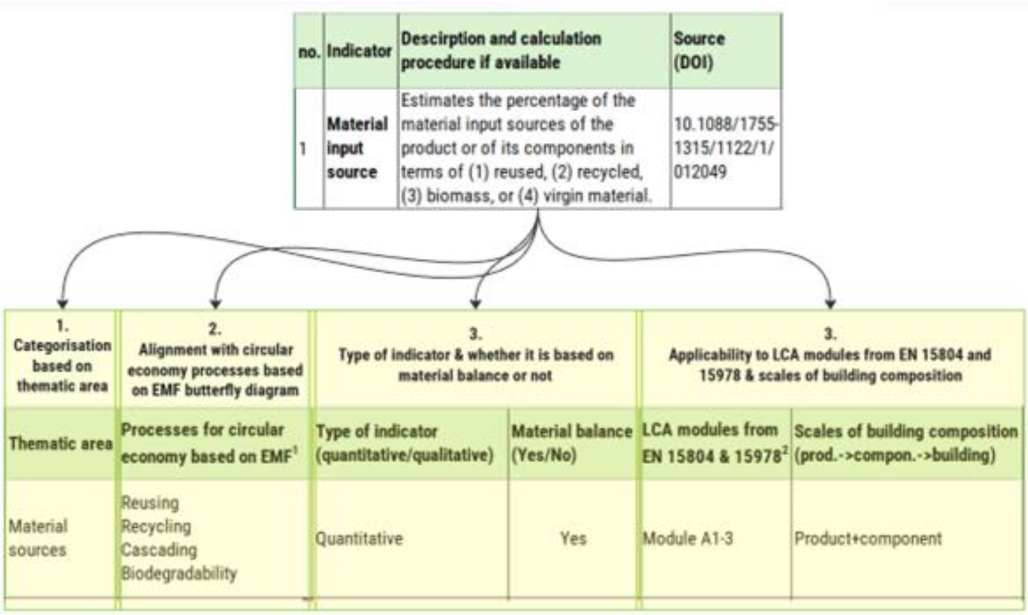
- **Stage 2: Literature review on circularity analysis**

Corresponding to the first subtask 4.6.1 of WP4, this stage carries out a literature review of circularity indicators (CIs) as a basis for defining the most relevant parameters for assessing circularity in the next phases.

It was conducted using a two-steps methodology, where for the first step the circularity analysis in the existing European projects, standardisation works and regulations was assessed. The findings of this analysis are detailed in Section 4.1, highlighting the necessity for a clear distinction between CIs at different scales of building composition due to objectives of BIO4EEB project. Building on the insights from the first step, a systematic literature review (SLR) was conducted to evaluate CIs available in the scientific literature, as outlined in Section 4.2. The review identified an extensive range of CIs, which are comprehensively listed in Table A1 (Annex A). Collected CIs from scientific literature are then utilised for development of the circular referential analysis.

- **Stage 3: Development of a circular referential analysis**

Based on the literature review, this stage consists of a detailed analysis and description of the indicators selected as the most appropriate for assessing circularity in the context of the project. It corresponds to the second subtask 4.6.2 of the WP4 and is detailly described in Chapter 5. The shortlisted CIs are characterized in Sections 5.2.2.3 and 5.2.2.4. These CIs are compiled in an Excel sheet (**Fehler! Verweisquelle konnte nicht gefunden werden.**) that provides a comprehensive characterization based on the steps outlined in Section 5.1.2 (*Methodology for circularity indicators assessment*). This Excel sheet will be shared with solution providers and demo case managers to facilitate the application of the most relevant CIs to BIO4EEB solutions, enabling the final validation of the decisions.



no.	Indicator	Descirption and calculation procedure if available	Source (DOI)
1	Material input source	Estimates the percentage of the material input sources of the product or of its components in terms of (1) reused, (2) recycled, (3) biomass, or (4) virgin material.	10.1088/1755-1315/1122/1/012049

1. Categorisation based on thematic area	2. Alignment with circular economy processes based on EMF butterfly diagram	3. Type of indicator & whether it is based on material balance or not		3. Applicability to LCA modules from EN 15804 and 15978 & scales of building composition	
Thematic area	Processes for circular economy based on EMF[1]	Type of indicator (quantitative/qualitative)	Material balance (Yes/No)	LCA modules from EN 15804 & 15978[2]	Scales of building composition (prod.->compon.->building)
Material sources	Reusing Recycling Cascading Biodegradability	Quantitative	Yes	Module A1-3	Product+component

Figure 1 Extract form Excel sheet on shortlisted circularity indicators in accordance with the steps defined in Section 5.1.2

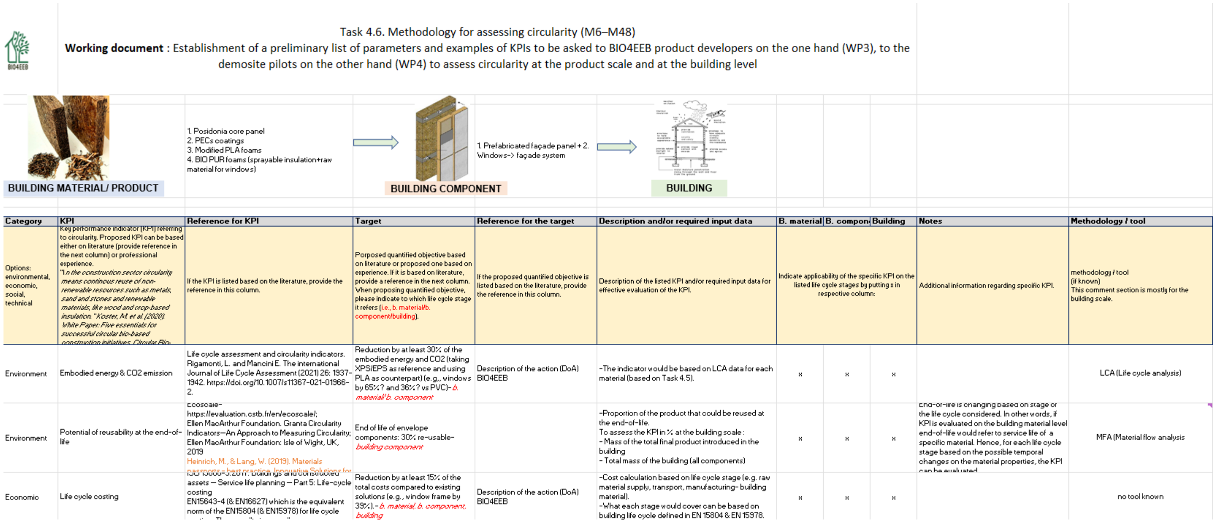
- **Stage 4: Development of a certification scheme**

The final stage of the methodology consists of developing the certification process by defining an assessment method based on the indicators selected in stage 3 and testing it to assess BIO4EEB solutions and democases.
This stage will be presented in the second version of this deliverable at M48.

3 Results of stage 1: Setting objectives

This first stage proved to be essential for framing the scope of the study and defining the input data and targeted outcomes of this 4.6 task. It enabled a consensus to be reached on the scope to be studied, taking into account the broader objectives of BIO4EEB, to frame the work to come and to provide the WP3 technical partners and the WP4 demo-managers with the initial information they needed.

These initial exchanges resulted in a preliminary list of examples of circular indicators being disseminated via Focchi to the WP3 partners. Joint work with the CEU (as task leader of T4.5 - Life Cycle Assessment for each developed solution components) on this initial list enabled the circular approach to be well differentiated from the LCA outputs and any overlaps to be identified. Overall, this initial approach helped to define the framework for the rest of the study.



Category	KPI	Reference for KPI	Target	Reference for the target	Description and/or required input data	B. material	B. compon	Building	Notes	Methodology / tool
Options: environmental, economic, social, technical	Key performance indicator (KPI) referring to circularity. Proposed KPI can be based either on literature (provide reference in the next column) or professional experience. "*In the construction sector circularity means continous reuse of non-renewable resources such as metals, sand and stones and renewable materials, like wood and crop-based insulation.*" *Koster, M. et al. (2020). White Paper: Five essentials for successful circular bio-based construction initiatives. Circular Bio-*	If the KPI is listed based on the literature, provide the reference in this column.	Porposed quantified objective based on literature or proposed one based on experience. If it is based on literature, provide a reference in the next column. When proposing quantified objective, please indicate to which life cycle stage it refers (i.e., b. material/b. component/building).	If the proposed quantified objective is listed based on the literature, provide the reference in this column.	Description of the listed KPI and/or required input data for effective evaluation of the KPI.	Indicate applicability of the specific KPI on the listed life cycle stages by putting x in respective column:			Additional information regarding specific KPI.	methodology / tool (if known) This comment section is mostly for the building scale.
Environment	Embodied energy & CO2 emission	Life cycle assessment and circularity indicators. Rigamonti, L. and Mancini E. The international Journal of Life Cycle Assessment (2021) 26: 1937-1942. https://doi.org/10.1007/s11367-021-01966-2.	Reduction by at least 30% of the embodied energy and CO2 (taking XPS/EPS as reference and using PLA as counterpart) (e.g., windows by 65%? and 36%? vs PVC)- *b. material/ b. component*	Description of the action (DoA) BIO4EEB	-The indicator would be based on LCA data for each material (based on Task 4.5).	x	x	x		LCA (Life cycle analysis)
Environment	Potential of reusability at the end-of-life	Ecoscale- https://evaluation.cstb.fr/en/ecoscale/; Ellen MacArthur Foundation. Granta Circularity Indicators—An Approach to Measuring Circularity; Ellen MacArthur Foundation: Isle of Wight, UK, 2019 Heinrich, M., & Lang, W. (2019). Materials passports - best practice. Innovative Solutions for	End of life of envelope components: 30% re-usable- *building component*		-Proportion of the product that could be reused at the end-of-life. To assess the KPI in % at the building scale : - Mass of the total final product introduced in the building - Total mass of the building (all components)	x	x	x	End-of-life is changing based on stage of the life cycle considered. In other words, if KPI is evaluated on the building material level end-of-life would refer to service life of a specific material. Hence, for each life cycle stage based on the possible temporal changes on the material properties, the KPI can be evaluated	MFA (Material flow analysis
Economic	Life cycle costing	ISO 15686-5:2017. Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing EN15643-4 (& EN16627) which is the equivalent norm of the EN15804 (& EN15978) for life cycle	Reduction by at least 15% of the total costs compared to existing solutions (e.g., window frame by 39%).- *b. material, b. component, building*	Description of the action (DoA) BIO4EEB	-Cost calculation based on life cycle stage (e.g. raw material supply, transport, manufacturing- building material). -What each stage would cover can be based on building life cycle defined in EN 15804 & EN 15978.	x	x	x		no tool known

Figure 2 Extract form Excel sheet on preliminary list of parameters and examples of circular KPIs

4 Results of stage 2: Literature review on circularity analysis

In an era where the construction industry is undergoing a paradigm shift towards more environmentally conscious methodologies, understanding the dynamics of circularity becomes imperative. Circular construction principles prioritise sustainable practices, emphasising circular design and the responsible use of materials to foster the application of circular materials (Metabolic, 2022a). As such, many circularity assessment methodologies focus on the way in which buildings are designed, and assessment of circularity of products is usually treated in the context of reversible building design or accessibility to different building layers without causing harm to allow for repair, replacement, reuse and recovery of products ("Reversible Building Design - BAMB," 2020). However, when it comes to the development of construction products, a unified approach for measuring circularity at product level is considered underdeveloped (Dräger et al., 2022).

The literature review on the CIs was conducted using a two-step methodology, where for the 1st step the circularity analysis in the existing European projects, standardisation works and regulations was assessed. In the second step the SLR was conducted involving the scientific literature.

4.1 Results of step 1: Existing European projects, standardization works and regulations

This section dives into understanding circularity in the European construction landscape. It aims to define the state of the art by collecting the main existing indicators and methods used to assess the circularity of construction products. To achieve this, it will study what has been used by recent relevant research projects, what are the current discussions in standardisation organisations, what is the current regulatory landscape, as well as some important initiatives that propose CIs mainly. The goal is to analyse previous or ongoing European research projects and standardisation activities, in order to characterise the usual scope of circularity for building composition and calculation methods for existing indicators. It includes a review of key research projects related to circularity in construction, standardisation efforts by bodies such as CEN/TC 350 and ISO/TC 323, relevant EU regulations and directives, and other significant initiatives and frameworks proposing CIs.

Relevant sources were identified through a combination of database searches, targeted website visits, and expert consultations. Key databases and platforms included CORDIS (Community Research and Development Information Service) for European research projects, websites of standardisation bodies such as CEN and ISO, EU regulatory documents and directives, and major initiatives and frameworks related to circularity in construction. Keywords used in the search included "circular construction," "bio-based insulation," "circular economy," and "circularity indicators." Once the relevant documents were collected, they were explored in details in order to extract any relevant CIs that could be useful for measuring circularity in construction bio-based products.

The synthesis of findings involved integrating data from different sources to provide a comprehensive overview of the state of the art in CIs and methods. This synthesis included highlighting key indicators and methodologies identified across various projects and frameworks and identifying commonalities in approaches to assessing circularity.

The methodology acknowledges certain limitations. There is potential bias in the selection of sources due to the availability of information. Additionally, the dynamic nature of regulations and standards may lead to changes during the course of the review. Limited access to proprietary data from some research projects and initiatives is also a constraint. The collected data is structured in sections related to research projects, standardization works, EU regulations and other initiatives.

4.1.1 European research projects

The section will introduce completed research projects that are deemed relevant, together with their key achievements, showcasing real-world implementations of circular principles in construction. These projects explore various aspects such as bio-based insulation, circularity in construction, and deep renovation processes. The central focus of our exploration lies in the methodologies and indicators used by these projects to assess circularity. By delving into their approaches, the chapter aims to uncover the key metrics and evaluation methods employed in measuring circularity.

4.1.1.1 Selection of collected European projects

The selection of projects was done after research in the CORDIS database, where keywords such as “circular construction” and “bio-based insulation” led to some projects, and those with relevant deliverables are included below.

Table 1 Collected European projects

Project name (website)	Duration	Description
ISOBIO (http://isobioproject.com/project/)	2015-2019	A Horizon 2020 project, which developed a new approach to insulation materials through the combination of existing bio-derived aggregates with low embodied carbon with innovative binders to produce durable composite construction materials.
HOUSEFUL (https://houseful.eu/)	2018-2023	A Horizon 2020 project aimed to develop innovative circular solutions and services for new business opportunities in the EU housing sector by implementing sustainable practices and technologies.
CIRCuIT (https://www.circuit-project.eu/)	2019-2023	A research and innovation program funded by the European Union's Horizon 2020 program. It aimed to enhance knowledge and resource-sharing across the entire built environment value chain in four cities: Copenhagen, London, Hamburg, and Helsinki.
DRIVE 0 (https://www.drive0.eu/)	2019-2023	A Horizon 2020 project which aimed to accelerate deep renovation processes by enhancing a consumer-centred circular renovation process, making deep renovation

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Project name (website)	Duration	Description
		more attractive, environmentally friendly and cost effective.
Construction BLUEPRINT (https://constructionblueprint.eu/)	2019-2022	A project funded by the Erasmus+ Programme, is a collaborative initiative aimed at addressing the evolving educational needs of the construction industry within Europe.
REFLOW (https://reflowproject.eu/)	2019-2022	Funded by the European Union’s Horizon 2020 research and innovation program, the project focuses on developing solutions that support circular economy practices in urban areas.
BAMB (https://www.bamb2020.eu/)	2015-2018	Funded by the European Union's Horizon 2020 research and innovation programme, it aims to facilitate a transition to a circular economy within the construction industry, through enabling the reuse and recycling of building materials.
CityLOOPS (https://cityloops.eu/)	2019-2023	Funded by the EU Horizon 2020 program, aims at fostering circular economies in European cities to combat climate change and biodiversity loss.
METABUILDING (https://www.metabuilding-project.eu/)	2020-2023	A Horizon 2020 EU Innovation project that aims to empower EU Construction SMEs by fostering cross-sectoral collaboration, facilitating innovation, and supporting their internationalisation efforts, ultimately contributing to their competitiveness and resilience in the face of challenges such as the COVID-19 crisis.
MOBICCON-PRO (https://mobiccon-pro.eu/)	2022-2027	A Horizon Europe project which will develop, introduce and demonstrate integrated innovative circular solutions to recover resources from construction and demolition waste (CDW) and decrease consumption of raw construction materials by applying in-situ selective separation/demolition, novel CDW recycling and production of recycled and innovative construction materials, components and products.
BioBUILD (https://bio-build.eu/)	2024-2027	Funded by Horizon Europe, project represents an effort towards enhancing the sustainability and efficiency of contemporary building practices.

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4.1.1.2 Addressing of circularity in the European projects

In this section the description of the methodologies in addressing circularity of the collected European projects is provided as follows:

- **ISOBIO**

The project used life cycle assessment (LCA) methodology to assess the environmental impact of the developed materials, including indicators such as embodied energy, embodied carbon, and end-of-life scenarios. The LCA methodology used in the project considers the entire life cycle of the materials and their potential for reintegration into the economy at the end of their useful life. Additionally, the project used life cycle costing (LCC) methodology to assess the economic performance of the materials, including indicators such as capital costs, operational costs, maintenance costs, and end-of-life costs. The project's assessment methodology took into account the principles of circularity by evaluating the potential for re-use, recovery, and recycling of materials at the end of their life, and by minimising waste and maximising resource efficiency throughout the life cycle of the materials. The assessment is based mainly on qualitative assessment, using different end-of-life scenarios.

- **HOUSEFUL**

The assessment method developed within the project aimed to provide a robust and reliable means of quantifying the degree of circularity in the housing sector, both pre- and post-refurbishment. This method was designed to be user-friendly and applicable to daily market practices, catering to a wide range of stakeholders including designers, construction companies, promoters, and financial institutions. It took into account key circular economy principles such as recyclability, reusability, and waste savings of materials, as well as the feasibility of circular solutions offered as services to stakeholders. The assessment method also considers existing or new methodologies related to circularity vectors, including LCC, LCA, and Social Life Cycle Assessment (S-LCA) methodologies. The results obtained were used to develop an integrated HOUSEFUL service which is driven and promoted through a Software as a Service (SaaS). The SaaS integrates a Circularity Tool to quantify the circularity level of buildings and includes different circular solutions offered as services, encouraging the housing value chain to redesign traditional business models towards circular ones. The Circularity tool can be found here: https://houseful.iris-eng.com/public/circularity_tool

- **CIRCuIT**

The CIRCuIT project has identified a comprehensive set of CIs designed to measure and assess the circular economy performance at the city, building, and material levels. These indicators encompassed impact metrics such as recycled content and material use, productivity metrics including per value and area, and enabler metrics such as the number of projects with circular economy requirements. The indicators were intended to provide a robust and concise overview of circularity, enabling stakeholders to make informed decisions and support evidence-based policy and planning development. Additionally, they can be used to measure the environmental, economic, and social impact of circular economy decisions and validate their benefits using assessment methods such as LCA, LCC, and social impact approaches.

- **DRIVE 0**

The assessment method employed in the project encompassed two levels of evaluations to gauge the circularity potential of products and materials. The Level 1 assessment offered a rapid overview of circularity based on a series of yes/no questions, enabling a swift analysis of a product's foundational circularity. In contrast, the Level 2 assessment delved deeper, incorporating a comprehensive set of indicators to provide in-depth insights into the circularity level of a product and its potential for improvement. These assessment methods were underpinned by the Design for Disassembly (DfD) methodology. The CIs used in the second level, encompassed a range of metrics to evaluate their circularity potential. For this assessment, a significant amount of data is necessary, as well as a higher level of experience/knowledge of the assessor. Importantly, the project developed a rating system based on the criteria of DfD, and this rating was included as an indicator for circularity.

- **Construction BLUEPRINT**

While the project did not explicitly develop CIs, it is intricately linked to the circularity in construction by promoting sustainable practices and the implementation of circular economy principles through its vocational education and training programs. By identifying skill gaps and fostering innovation, the project aims to enhance the industry's capacity to adopt resource-efficient methods, reduce waste, and maximise the reuse and recycling of materials. This initiative supports the transition towards a more sustainable construction sector, ensuring that future professionals are well-equipped to contribute to a circular economy.

- **REFLOW**

In relation to circularity in construction, REFLOW emphasises the importance of rethinking traditional linear models of production and consumption in the building industry. The project promotes the use of recycled materials, the extension of the lifespan of buildings, and the implementation of modular design approaches that facilitate easy disassembly and reuse of components. These practices help reduce waste, lower carbon emissions, and decrease the overall environmental impact of construction activities.

- **BAMB**

A key element of BAMB project was the creation of materials passports, which serve as a centralised platform for storing and sharing detailed information about building materials, thus promoting resource efficiency and sustainability in the built environment. A materials passport is a digital dataset that catalogues the essential characteristics of materials and components used in construction products and systems. These passports provide comprehensive information on aspects such as physical properties, chemical composition, biological attributes, material health, and unique product identifiers. The data contained within a materials passport is crucial for assessing the potential for recovery, reuse, and recycling of building materials, thereby extending their lifecycle and maintaining their value over time. Materials passports are integral to the circularity of products by providing the necessary indicators that assess and enhance the sustainability of building materials. These indicators include properties that determine the ease of disassembly, the potential for material recovery, and the environmental impact of materials throughout their lifecycle. By offering detailed insights into the composition and performance of materials, materials passports facilitate circular product design and resource management.

- **CityLOOPS**

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Seven cities across Europe are used as pilot sites, focusing on closing material loops and transforming their economies toward sustainability. These actions are supported by an Urban Circularity Assessment (UCA) method developed within the project, which evaluates cities' circularity status and the effectiveness of their initiatives. The method employs material flow and stock accounting, complemented by system-wide indicators, to assess a city's circularity status comprehensively. Material flow accounting covers the entire local economy, categorised into six material groups, with specific materials studied along the supply chain. This analysis provides a detailed understanding of material flows and their circularity within the city. Additionally, material stock accounting focuses on municipal buildings, offering insights into the city's built environment. The UCA method's mass-based CIs enable cities to assess their circularity performance and identify areas for improvement, providing a practical tool for urban policymakers and practitioners to guide their transition towards greater material circularity.

- **METABUILDING**

By incorporating Circular & Recycling Industries as one of its targeted industrial sectors, the project acknowledges the imperative of circular practices within construction. METABUILDING aims to catalyse innovation that embraces circular principles, such as material reuse, recycling, and resource efficiency. Through the collaborative projects and the establishment of a Digital Platform, METABUILDING facilitates the adoption of circular solutions among SMEs, enabling them to reduce waste, minimise environmental impact, and create more resilient built environments. Furthermore, by fostering collaboration across sectors, METABUILDING encourages the integration of circular practices throughout the construction lifecycle, from design and manufacturing to end-of-life processes, thereby contributing to a more sustainable and circular economy overall.

- **MOBICCON-PRO**

Project concept includes two key elements for success: the Territorial Circularity Centre and a mobile waste management scheme based on separate collection technologies and a mobile waste treatment pilot facility.

- **BioBUILD**

The project aims to provide thermal solutions for energy-efficient buildings primarily using bio-based materials. BIOBUILD is incorporating bio-based phase change materials (bioPCMs) into building materials like solid wood and fibers, using plant oil resins, lignin, and fungal mycelium. By adding bioPCMs, it aims to cut energy use in buildings by up to 20%. The project also explores better insulation using lightweight, recyclable materials. It plans to test these innovations in wooden houses in Sweden and Spain to prove their effectiveness. The overall aim is to reduce the environmental impact of construction and promote the use of bio-based materials, contributing to decarbonisation efforts.

Table 2 presents the CIs associated with the listed projects, alongside the assessment addressed in each specific project. The data highlights the significant emphasis placed on tools for sustainability assessment within the construction industry, including methodologies such as LCA, LCC, and S-LCA. Moreover, the indicators related to recycling are included in six out of the 11 projects analysed, highlighting the industry’s strong focus on recycling practices as a key aspect of circularity assessments, while reuse receives comparatively less attention (addressed in only four projects). However, the scopes of these projects vary significantly across different assessment scales, ranging from products and buildings to entire cities. This variability underscores the need for further investigation into CIs through a more comprehensive review of scientific literature. The indicators currently available in European

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projects remain limited and highly case-dependent, emphasising the importance of expanding and standardising these metrics for broader and more consistent application.

Table 2 Collected European project and relevant circularity indicators

Project	Assessment level	Relevance to circular economy indicators
ISOBIO	Product	Embodied energy, embodied carbon, end-of-life scenarios, waste minimization
HOUSEFUL	Product, Building	Recyclability, reusability, waste savings, LCA, LCC, S-LCA
CIRCuIT	Product, Building, City	Recycled content, material use, productivity metrics
DRIVE 0	Product	Design for Disassembly, material division, repairability
Construction BLUEPRINT	Building	Resource-efficient methods, waste reduction, material reuse
REFLOW	Product, Building, City	Recycling rate, material reuse, environmental impact reduction
BAMB	Product, Building	Design for Disassembly, material health, recycled content
CityLoops	City, Product	Material flow accounting, stock accounting, circularity performance
METABUILDING	Building	Material reuse, recycling, resource efficiency
MOBICCON-PRO	Product	Resource recovery, waste reduction, recycling rate
BIOBUILD	Product	Energy use reduction, bio-based material utilization

4.1.2 Standardisation works

While numerous environmental standards have been developed to address sustainability in construction, two technical committees have played a significant role in establishing standards that address the environmental aspects of construction and promote sustainability. **CEN/TC 350**- **Sustainability of construction works** is responsible for developing horizontal standardised methods for the assessment of sustainability aspects in the construction sector, covering both new and existing construction works, which encompass buildings and civil engineering projects. More specifically, **ISO/TC 323- Circular Economy** specializes in circular economy standardisation, providing guidance and tools to support organisations in implementing circular practices. It works collaboratively with other committees on subjects relevant to circular economy initiatives. These two committees, together establish a solid foundation for the development of standards that guide sustainable construction practices, including the consideration of CIs and assessments within the broader context of environmental performance and sustainability. This chapter aims to provide an overview of the most important standards developed by the abovementioned committees together with the available indicators provided in Table 3.

Standards developed in **CEN TC/350** are **EN 15804:2012+A2:2019- Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products** (CEN, 2022) and **EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method** (CEN, 2011). The European Standard EN 15804:2012+A2 provides core

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product category rules for Type III environmental product declarations (EPDs) for any construction product and construction service. It describes how to calculate the environmental performance of a construction product across its entire life-cycle. EPDs offer a comprehensive means to communicate the environmental performance of products, enabling stakeholders to make informed decisions based on quantified data using set of indicators including climate change, ozone depletion, acidification, eutrophication, etc. (CEN, 2022). **EN 15804+A2** addresses circularity by incorporating module D into its methodology. Module D is regarded as essential for assessing the potential for recycling and reuse at the end of a building element's life, providing insights into its "circularity potential." However, according to (Van Gulck et al., 2022), challenges and uncertainties are associated with module D, especially when dealing with reused products, making its interpretation complex. The study suggests that alongside module D, considering multiple use cycles through transformations in module B5 can enhance the assessment of circularity. Module B5 allows for the evaluation of reuse during a building element's lifespan, providing a more practical approach to circularity assessment (Van Gulck et al., 2022).

The **EN 15978** provides a comprehensive framework for evaluating the environmental performance of buildings. In addition to LCA, the standard incorporates other quantified environmental data that are essential for a thorough assessment. This may include data related to energy consumption, water usage, greenhouse gas (GHG) emissions, waste generation, and other environmental indicators. By integrating a wide range of environmental data, **EN 15978** ensures that the assessment process provides a holistic view of a building's environmental performance. This approach encompasses all stages of a building's life cycle, including construction, operation, and end-of-life considerations. By leveraging data from EPDs and their "information modules" as defined in **EN 15804**, along with other pertinent information, the standard ensures a thorough and standardized assessment process.

Moreover, standards developed in **ISO/TC 323 encompass** ISO 20887:2020 – Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance (ISO, 2020), **ISO 21930:2017 - Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services** (ISO, 2017), **ISO/DIS 59040- Circular economy — Product circularity data sheet** (ISO, 2023) and **ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework** (ISO, 2006). ISO **14040:2006** describes the principles and framework for LCA including: definition of the goal and scope of the LCA, the life cycle inventory analysis phase, the life cycle impact assessment phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. The actual mechanics of analysis (such as data collection or calculation) are not included but are left to the practitioners. As such, ISO **14040** does not specify particular indicators but establishes the structure and requirements for conducting LCAs, and indicators are selected based on the specific goals and scope of the assessment. Moreover, the **ISO 21930** is the global standard that provides the principles, specifications and requirements to develop an EPD for construction products and services, construction elements and integrated technical systems used in any type of construction works.

In particular, **ISO 20887:2020** addresses circularity practices in the construction industry as a standard of design for disassembly and adaptability (DfD/A). It encompasses a general vocabulary, definitions, and guidelines, catering to the needs of stakeholders such as owners, architects, engineers, product designers and manufacturers. The primary goal is to

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facilitate the easier reuse of components and the recycling of materials when reuse is no longer feasible. Despite the comprehensive nature of ISO 20887, concerns are raised about the general and vague nature of the guidelines, questioning their practical applicability. The standard provides an essential foundation, but stakeholders may need additional specific guidance to effectively implement DfD/A principles in practice (Anastasiades et al., 2021). Moreover according to **ISO/DIS 59040** The Product Circularity Data Sheet (PCDS) is a standardised template designed to provide reliable and consistent data on the circularity of products. Developed through the Circularity Dataset Standardization Initiative launched by the Ministry of the Economy of Luxembourg, the PCDS aims to facilitate the global exchange of circularity information (Mulhall et al., 2022). It supports the objectives of the circular economy by offering a decentralized, open-source template that includes basic circularity criteria. The PCDS template can be completed in a fillable PDF format or machine-readable formats such as XML or JSON. The PCDS is intended to be used across different sectors, providing a unified approach to reporting and sharing product circularity data. Based on the collected standards it can recognized that construction industry is lacking a specific methodology for circularity assessment.

Table 3 Indicators relevant to sustainability (including circularity)

Indicator	Unit	Reference
Global warming potential total (GWP-total)	kg CO_2 eq.	(CEN, 2022, 2011)
Use of secondary material	kg	(CEN, 2022, 2011)
Use of renewable secondary fuels	MJ, net calorific value	(CEN, 2022, 2011)
Use of non-renewable secondary fuels	MJ, net calorific value	(CEN, 2022, 2011)
Components for re-use	kg	(CEN, 2022, 2011)
Materials for recycling	kg	(CEN, 2022, 2011)
Materials for energy recovery	kg	(CEN, 2022, 2011)
Percentage of reclaimed content	% (by weight or volume)	(ISO, 2020)
Value of reclaimed content	Monetary value	(ISO, 2020)
Percentage of recycled content	% (by weight or volume)	(ISO, 2020)
Value of recycled content	Monetary value	(ISO, 2020)
Practically reusable (yes or no)	Binary (yes/no)	(ISO, 2020)
Practically recyclable (yes or no)	Binary (yes/no)	(ISO, 2020)
Reuse grading	Continuum (ranging from entire structure to selected materials)	(ISO, 2020)
Refurbishability assessment (yes or no)	Binary (yes/no)	(ISO, 2020)
Remanufacturability assessment (yes or no)	Binary (yes/no)	(ISO, 2020)
Recyclable content	%	(ISO, 2023)

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Indicator	Unit	Reference
Recycled content	%	(ISO, 2023)
Biodegradable content	%	(ISO, 2023)
Ease of disassembly	Binary (Y/N)	(ISO, 2023)
Expected lifespan	years	(ISO, 2023)
Reuse potential	Binary (Y/N)	(ISO, 2023)
Remanufacturing potential	Binary (Y/N)	(ISO, 2023)
Presence of hazardous materials	Binary (Y/N)	(ISO, 2023)
Carbon footprint	CO_2e (kg)	(ISO, 2023)
Water usage	Litres	(ISO, 2023)

4.1.3 European Union Regulations

Three EU regulations have been identified as relevant for circularity assessment as follows:

1. Construction product regulation (CPR) (305/2011);
2. Energy Performance of Buildings Directive (2018/844);
3. Waste framework directive (2008/98).

The CPR establishes harmonized rules for the marketing of construction products within the EU. While the CPR primarily focuses on product performance and safety, it also encourages the consideration of environmental aspects, including CIs. Specifically, when setting the basic requirements for construction works, it indicates that they should be designed, built, and demolished with a focus on sustainable use of natural resources, emphasising the reuse or recyclability of materials, the durability of the construction, and the use of environmentally compatible raw and secondary materials. The ongoing revision of the CPR is expected to establish stronger sustainability product requirements aiming to reduce the environmental impact of products.

The Energy Performance of Buildings Directive aims to improve the energy efficiency of buildings within the European Union. While the directive primarily focuses on energy performance requirements, it also promotes the use of sustainable materials and encourages the consideration of LCAs in the construction and renovation of buildings. Its ongoing revision aims to ensure that the EU's building stock will be carbon-free and energy efficient by 2050.

The Waste Framework Directive establishes the legal framework for waste management in the EU, including construction and demolition waste (CDW). It promotes waste prevention, recycling, and the use of recycled materials, which aligns with circular economy principles. The directive may indirectly encourage the consideration of CIs in construction product design and material selection.

4.1.4 Other initiatives

4.1.4.1 Ellen MacArthur Foundation circularity indicators

The Ellen MacArthur Foundation (EMF) conducted a research to describe a methodology for assessing the circularity of companies' flows of products and materials, which allows companies to understand how far they are on transitioning their products from linear to circular. The methodology provides a frame of reference for discussing how circular a product is and how circularity impacts other objectives, but it does not directly incorporate other metrics such

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as viable business models, lower business risks, or improved social equity (Goddin et al., 2019).

The methodology provides a set of suggested complementary indicators, which are classified into complementary risk and impact indicators (Table 4). These indicators represent a non-exhaustive list of the types of metrics among which circularity is likely to be considered. Some of the methodologies for calculating these complementary indicators may require adjustment to appropriately represent circular systems, as many have been established on the basis of measuring linear models.

Table 4 Circularity indicators included in Ellen MacArthur Foundation methodology

Indicator	Unit
Material circularity Indicator	%
Product circularity Indicator	%
Waste circularity Indicator	%
Reuse index	%
Recycling index	%
Linear flow index	kg/kg

These CIs are used to measure the circularity of a product or company. The Material circularity Indicator (MCI) is one of the most appreciated CIs for product-level evaluation (Rigamonti and Mancini, 2021). It measures the proportion of recycled or renewable materials in a product. Moreover, the Product circularity Indicator measures the proportion of a product that can be reused, repaired, or remanufactured. The Waste circularity Indicator measures the proportion of waste that can be recycled or biodegraded. The Reuse and Recycling Indices measure the proportion of a product that is reused or recycled at the end of its life. Finally, the Linear flow index measures the amount of material inputs required to produce a unit of product output.

4.1.4.2 Level(s)

Level(s) is a voluntary reporting framework developed by the Joint Research Centre (JRC) of the European Commission, to improve the sustainability of buildings. Using existing standards such as EN 15804, Level(s) provides a common EU approach to the assessment of environmental performance in the built environment. The Level(s) common framework is based on six macro-objectives that address key sustainability aspects over the building life cycle, with one of them focusing on resource efficient and circular material life cycles. Those are:

1. Greenhouse gas emissions along a buildings life cycle;
2. Resource efficient and circular material life cycles;
3. Efficient use of water resources;
4. Healthy and comfortable spaces;
5. Adaption and resilience to climate change;
6. Optimised life cycle cost and value.

Since 2nd objective is directly correlated with the circularity, the indicators associated with this macrobjective will be presented below.

4.1.4.2.1 Bill of quantities, materials, and lifespan

(Honic and De Wolf, 2023) applied Bill of quantities, material, and lifespans to a case study in order to facilitate a more profound comprehension of the utilisation of Level(s) framework indicators in practice (Figure 3). The Excel template and Calculation and Assessment Tool (CAT) have been provided for the purpose of conducting an assessment of this indicator. The colouring of the template is based on the distinction between mandatory and optional cells, with the former indicated by green and the latter by yellow. The results are displayed in red. Additionally, an optional cost and lifetime assessment is available (Honic and De Wolf, 2023). In summary, this indicator enables the conversion of a bill of quantities into a bill of materials, the calculation of costs for each material, and the allocation of specific lifetimes for building materials or elements relative to the planned lifetime of a building. The output regarding the building material is expressed in tonnes or as a percentage of the total mass, with the material types (e.g., concrete, wood, metals) and building aspects (e.g., shell, core, external) being distinguished (Donatello and Dodd, 2021). In essence, the indicator offers insight into the materials employed in the construction, potentially accompanied by cost data and projected lifespans. However, it does not take into account certain parameters that affect the circularity of building materials, as acknowledged by (Honic and De Wolf, 2023). It can be applied at a building scale with a particular focus on LCA module A1-3 (Table 5).

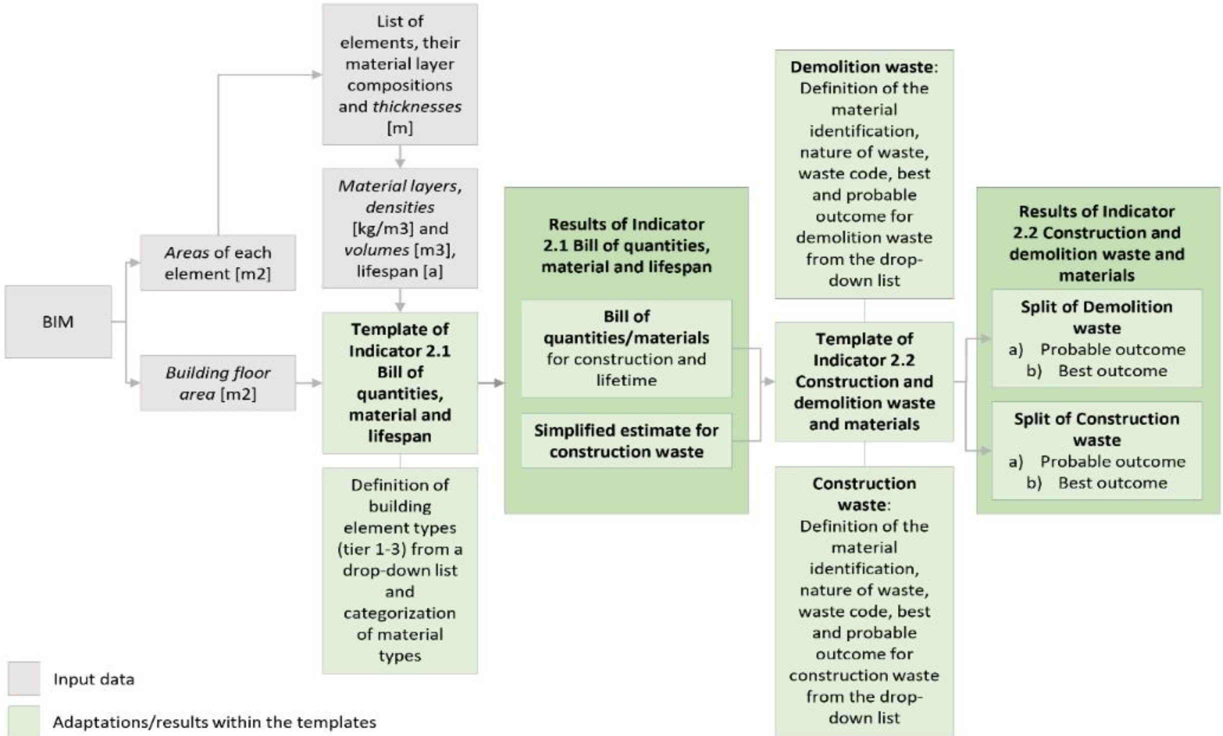

Figure 3 Input data and workflow for Bill of quantities, material and lifespan and Construction and demolition waste and materials indicators from Level(s) (Honic and De Wolf, 2023)

4.1.4.2.2 Construction and demolition waste and materials

Similarly to the Bill of quantities, materials and lifespan, (Honic and De Wolf, 2023) applied this indicator to a case study in order to facilitate a more profound comprehension of the utilisation of Level(s) framework indicators in practice (Figure 3). The template for this indicator is directly related to that of the previous one. In particular, the mass of each material layer, the material type, the estimated wastage rate, the waste type and the waste core are obtained from the Bill of quantities, materials and lifespan. It is possible to consider both construction and demolition waste (Honic and De Wolf, 2023). The resulting output is based on the mass allocation of materials, with consideration given to the end-of-life waste management options, including reuse, recycling, material recovery (backfill), energy recovery, and disposal (inert, non-hazardous, or hazardous) (Dodd and Donatello, 2020). (Honic and De Wolf, 2023) identified a limitation of the indicator in not accounting for potential differences in recycling and reuse capabilities due to varying connection types, as well as in classifying all insulations as hazardous waste. However, the indicator can address A4-5, B3-5 and C modules, given the possibility of waste generation at these stages at the building scale (Table 5).

4.1.4.2.3 Design for adaptability and renovation

(Askar et al., 2024) examined how Level(s) addresses Design for adaptability, a circular strategy focused on intentionally designing buildings to accommodate changes throughout their lifecycle. With regard to the macro-objectives of Resource efficient and circular material life cycle an indicator specifically addressing the Design for adaptability and renovation (Askar et al., 2024). The indicator is semi-quantitative and focuses on the design and service features tailored to two building types: office buildings (with a particular emphasis on flexibility within the office market and changing use within the property market) and residential buildings (with a particular emphasis on changes in family and personal circumstances and changing use with the property market). The indicator can be applied at three levels:

- Level 1 (Conceptual design) – The checklist is used to assess whether a specific adaptability design concept has been addressed in accordance with the design principles. A "Yes" or "No" response is provided, accompanied by a brief description of how.
- Level 2 (Detailed design and construction) – The scoring of each design aspect addressed is conducted based on the drawings and dimensions provided. A weighting factor is then applied to obtain a score out of 100.
- Level 3 (As-built and in-use) – Based on the final design features and an inspection, the scoring of each design aspect addressed is conducted, and a score out of 100 is obtained using a weighting factor (Dodd and Donatello, 2021a)**.**

As identified by (Askar et al., 2024), the majority of the adaptability requirements are addressed, although certain limitations exist, particularly with regard to the inclusion of material-scale specifications. However, at the building scale, the criteria addressed are comprehensive, encompassing A and B LCA modules, with the exception of the production stage (Table 5).

4.1.4.2.4 Design for deconstruction

This indicator employs a semi-quantitative assessment methodology to evaluate the extent to which the building's design facilitates the future recovery of materials for reuse or recycling. A score is assigned to each of the three deconstruction aspects: ease of recovery, recycling and reuse (Dodd and Donatello, 2021b). (Incelli et al., 2023) investigated the applicability of the Design for deconstruction indicator. The findings emphasise the focus of the indicator on material flow data, which serves to simplify the complexity of circularity in multi-material buildings. However, the presence of different scales of building composition is not fully incorporated, with deconstruction aspects directly correlated with that of material (Incelli et al., 2023). Hence, this indicator directly addresses LCA modules A4-5, B3-5 and C at the building scale (Table 5).

Table 5 Circularity indicators conformity to LCA modules

Circularity indicator	LCA module
Bill of quantities, materials and lifespan	A1-3
Construction and demolition waste and materials	A4-5, B3-5, C
Design for adaptability and renovation	A4-5, B
Design for deconstruction	A4-5, B3-5, C

4.1.4.3 European Commission study on measuring the application of circular approaches in the construction industry ecosystem

In 2023, the European Commission published a study measuring the application of circular approaches in construction (European Commission et al., 2023). The study aimed to identify indicators that can be used to measure the uptake of circular approaches at different levels of the construction sector. It used a combination of mind-mapping exercises and expert interviews to identify and prioritize the indicators, resulting in a long list of potential indicators, which were then prioritised based on specific criteria, such as data and measurement methodology. The indicators can be use in four levels: product level, building or infrastructure level, organisational level, or urban level. In Table 6 recommended core indicators for product/material level as well as building/infrastructure level are provided.

Table 6 Recommended core indicators in (European Commission et al., 2023)

Indicator	Unit	Level of activity
Reused Product	Binary (Y/N)	Product or material level
Recycled/secondary content	% by mass	Product or material level
Predicted service life	Years	Product or material level
Hazardous Waste	% by mass	Product or material level
Realistic end of life scenarios developed	Binary (Y/N)	Product or material level
At concept stage: comparison of asset LCA	Depends on impact category, e.g., $kgCO_2$ eq/m^2/yr	Building or infrastructure level
At design stage: Material intensity/dematerialisation	kg/m^2/yr	Building or infrastructure level
At design stage: reused content	% by mass	Building or infrastructure level
At design stage: recycled content	% by mass	Building or infrastructure level
Designed for disassembly/deconstruction	% reuse potential by mass	Building or infrastructure level
Construction waste generated on and off site	tonnes/100k EUR	Building or infrastructure level
Construction waste reused, recycled, recovered, landfilled	% by mass	Building or infrastructure level
Demolition waste generated	tonnes	Building or infrastructure level
Demolition waste reused, recycled, recovered, landfilled	% by mass	Building or infrastructure level

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4.1.4.4 Cradle to Cradle certification

Cradle to Cradle (C2C) is a design approach developed by William McDonough and Michael Braungart, aiming for continuous improvement in product design. Instead of minimising negative environmental impacts, it seeks to leave a positive impact by integrating principles such as waste elimination, use of renewable energy, and consideration for social fairness (Llorach-Massana et al., 2015).

The C2C Certified program, managed by the Cradle to Cradle Products Innovation Institute ("Cradle to Cradle Products Innovation Institute," n.d.), evaluates products based on five quality categories:

- Material and Health: Evaluates materials for safety and impact on human health.
- Material Reutilisation: Focuses on the continuous reclamation and reuse of materials.
- Renewable Energy and Carbon Management: Emphasizes the use of renewable energy sources and effective carbon management.
- Water Stewardship: Examines the sustainable use and management of water resources.
- Social Fairness: Considers social aspects, including fairness and stakeholder considerations.

For each category, a score is given, which leads to the final certification of the product. The material reutilisation score evaluates how recyclable and sustainable materials are in a product. The score considers the percentage of materials that can be recycled or composted and those made from recycled or renewable sources. Achieving a material reutilization score of at least 35 indicates a commitment to designing products for either technological or biological cycles, with plans for recovery and processing.

4.1.4.5 Urban mining model

The Urban Mining model is an analytical tool used to quantify and evaluate the material stocks and flows within the built environment developed by Metabolic, an Amsterdam-based group of organisations working towards circular economy (Metabolic, 2024). This model operates on a bottom-up approach, starting with detailed data on individual buildings, including their material composition, construction techniques, and lifecycle stages. By aggregating this information, the model provides a comprehensive overview of the materials embedded in the existing building stock and predicts future material demands and waste generation. It also identifies opportunities for material recovery and reuse, supporting the transition to a circular economy. The Urban Mining Model is instrumental in assessing the environmental impacts of different renovation scenarios, helping to optimise resource efficiency and minimise GHG emissions in the building sector.

The model is used in the study of the European Environmental Bureau on modelling the renovation of buildings in Europe from a circular economy and climate perspective" (Metabolic, 2022b). The study quantifies the material flows and GHG emissions associated with building renovations, and then outlines various Circular Renovation Actions designed to reduce material consumption, increase the use of recycled and biobased materials, and promote the reuse of building components. The document aims to inform policymakers and stakeholders on effective strategies to achieve sustainability and circularity in the building sector.

4.1.4.6 Ecoscale

Ecoscale is an environmental assessment service provided by CSTB, aimed at characterising the circularity potential of construction products, equipment, and materials (CSTB, 2023). Ecoscale characterises construction products according to four indicators that cover the entire life cycle of the products: recycled and renewable material, demountability, reusability, and recyclability (Table 7). Each indicator is composed of several qualitative or quantitative criteria identified as leverage points, which are then weighted according to their importance to form the overall score. Products are graded from A to E based on their performance across these indicators, and the results are publicly accessible to assist construction stakeholders in identifying circular products and equipment.

Table 7 Indicators according to Ecoscale (CSTB, 2023)

Indicator	Unit
Recycled and renewable material	% of total material
Demountability	Binary (Y/N)
Reusability	Binary (Y/N)
Recyclability	Binary (Y/N)

4.1.5 Synthesis of step 1

This part of the literature review provided a comprehensive overview of CIs in the European construction landscape, focusing on the results from research projects, standardisation works, EU regulations, and other relevant initiatives. The synthesis chapter aims to weave together key findings from ongoing projects, standards, regulations, and initiatives, offering insights into challenges, commonalities, and the evolving landscape of circular construction practices.

Across the research projects presented in 4.1.1, there is a unified focus on LCA and LCC. Embodied energy, social impact, economic life cycle cost, and indicators related to reuse, recovery, and recycling consistently appear. These projects collectively emphasise the importance of evaluating circularity through a comprehensive lens, considering both environmental and economic dimensions.

On the other hand, standards from CEN/TC 350 and ISO/TC 323 provide a structured approach to circularity assessment. The standards presented offer methodologies for EPDs, design for disassembly, and LCA. Indicators like global warming potential, secondary material use, and recycling potential are common threads, providing a standardised basis for evaluating circularity in construction.

European regulations, including the Construction Products Regulation, Energy Performance of Buildings Directive, and Waste Framework Directive, showcase a regulatory push towards circular practices in construction. These regulations, while primarily addressing product performance, energy efficiency, and waste management, respectively, implicitly encourage sustainable material use and circularity.

Parallel to regulatory frameworks, various initiatives contribute to advancing circularity in the European construction landscape. These initiatives collectively emphasise crucial elements such as sustainable resource use, circular design principles, and life cycle considerations. Complementary to regulatory efforts, these initiatives offer further perspectives on circularity, encompassing systematic assessments, voluntary reporting frameworks, and continuous improvement in product design.

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4.2 Step 2: Systematic literature review

This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [26], which involved the utilisation of systematic literature review (SLR) methodology. The application of PRISMA has been demonstrated to provide users with a framework for evaluating the trustworthiness and applicability of review findings. In order to conduct a reliable SLR, it is essential to consider the following key steps: the selection of an appropriate database and keywords, as well as a comprehensive description of the eligibility criteria and methods for analysis (**Fehler! Verweisquelle konnte nicht gefunden werden.**). After two-stage screening process, where the first stage was based on the title, abstract and keywords screening and second one on full text analysis, the 65 papers were subjected for further assessment in the study. It is essential to emphasis that only articles that specifically focus on indicators related to the circularity of building products, components or the building as a whole will be considered. This means that any articles focusing on CIs related to higher levels of the built environment such as neighbourhoods, cities, regions, etc. were excluded.

Table 8 Characteristics of the search conducted

Date of conducting search	**Scientific database**	**Keywords and Boolean operators**	**Period considered**	**Search criteria**
3rd August 2024	Scopus	“building” AND “circular*” AND “indicator” OR “index*[1]”	2010-2024	Article title Abstract Keywords Written in English Articles Conference papers Book chapters Books

[1] A wildcard (*) was added to certain keywords to capture variations of terms, including different forms and related concepts.

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5 Results of stage 3: Development of a circular referential analysis

Based on a literature review on the European projects, standardization works and regulations (section 4.1), it has been recognised that there should be clear distinction between CIs on the distinct scales of building composition due to objectives of BIO4EEB project. This distinction arises from the diverse range of BIO4EEB solutions and their unique functions. For example, the Posidonia panel can serve as an insulation product for walls or be integrated into façade panels developed by GOYER. Each of these variants would then be applied to specific buildings with distinct characteristics (e.g., residential or office, refurbishment or new construction). The scales of building composition are defined as follows:

1. A **building material/product** is defined as any material or product that is used in construction. This includes, but is not limited to, steel, concrete, brick, masonry and glass. In this context, the terms “material” and “product” are used interchangeably, as some products are composed of multiple materials but are considered a single building material in the construction industry (e.g., fibrous insulation materials composed of one or more types of fibres together with binder material). For the sake of simplicity, this study will employ the term “building product”. In the majority of cases, manufacturers produce and market building products, which are defined as any product on the building that cannot be disassembled (Mayer and Bechthold, 2017).
2. A **building component/element** is a more complex unit than a building product. It is constituted by the assembly of multiple building products into a functional component of a building. In this study, the term “building component” will be employed. Building components are typically created by contractors and designers and comprise building products and connections (Mayer and Bechthold, 2017).
3. A **building** is defined as a structure that is either partially or fully enclosed and intended to be occupied for an extended period of time. It is distinguished from mobile structures and those not intended for occupancy (Harris, 2006).

Hence, in the rest of the document building product, component and building terms would be based on these definitions for a clear distinction.

Taking into account the review provided in section 4.1.2, it was clear that while LCA methodologies are well established, frameworks for assessing the circularity of buildings are still in the development stage with scattered methodological approaches and criteria (Askar et al., 2022; Fagone et al., 2023; Foster and Kerinin, 2020; Khadim et al., 2022; Oluleye et al., 2022; Ostapska et al., 2024). For example, the DfD of structures, recognised as one of the milestones in the circularity of buildings, is self-declared by architect/engineers due to the lack of standardised certification schemes (Ostapska et al., 2024). Identifying the available CIs, taking into account the postulates of the LCA methodology in EN 15804 and EN 15978 (CEN, 2022, 2011), seems to be the approach that could be most easily adopted in industry. It is of the utmost importance to evaluate the processes of each stakeholder in accordance with circularity principles in order to provide a transparent characterisation of a process or product as sustainable (Jayakodi et al., 2024). The involvement of different stakeholders is contingent upon the life cycle stage of a building. Material suppliers are involved in the product stage (A1-3), the construction process stage (A4-5) is correlated with a set of stakeholders (i.e., contractors, designers, consultants), and the use and end-of-life stages (B and C) are correlated with the client (Figure 4).

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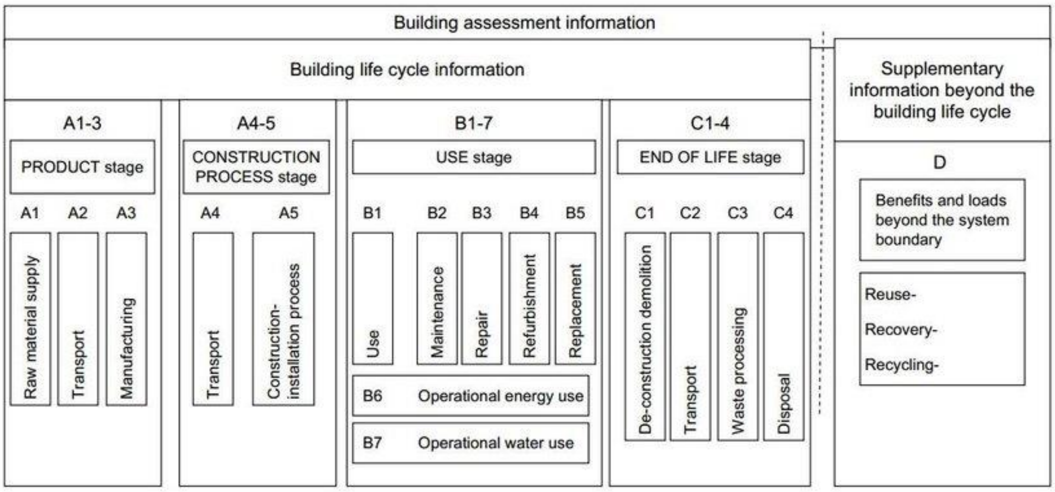

Figure 4 Building life cycle stages in accordance with EN 15804 and EN 15978 *(CEN, 2022, 2011)*

5.1 Research methodology

5.1.1 Science mapping

Bibliometric analysis was conducted to assess the trends and relationships in the research area of circularity indicators in the built environment. This was done using Excel to assess annual trends, geographical regions and amount of scientific papers correlated with specific EU funded projects.

5.1.2 Methodology for circularity indicators assessment

This review is exclusively based on papers sourced from the Scopus database. However, some of the indicators presented here have been adapted from commercially available tools and frameworks that are widely used in the literature. For the sake of simplicity in assessment, we have not distinguished between CIs developed in the cited papers and those adopted from previous publications. In most cases, the original source of each indicator is provided; if omitted, relevant references can be found in the corresponding publications. The indicators for embodied energy and carbon, which consider the end-of-life stage, have been excluded due to these indicators being part of LCA.

In order to provide a more detailed and accurate characterisation of the collected and shortlisted CIs, the following steps are taken:

1. A categorisation based on the thematic areas on which they focused was undertaken.
2. The shortlisted CIs from each thematic area are presented and characterised according to the circular economy process outlined in the EMF butterfly diagram (Figure 5).
3. The shortlisted CIs are characterised according to their type (qualitative or quantitative) and whether they are based on material balance.
4. Detailed description of the shortlisted indicators and their applicability to LCA modules (in accordance with EN 15804 and EN 15978 (CEN, 2022, 2011)) and scales of building composition (i.e., product, component, building).

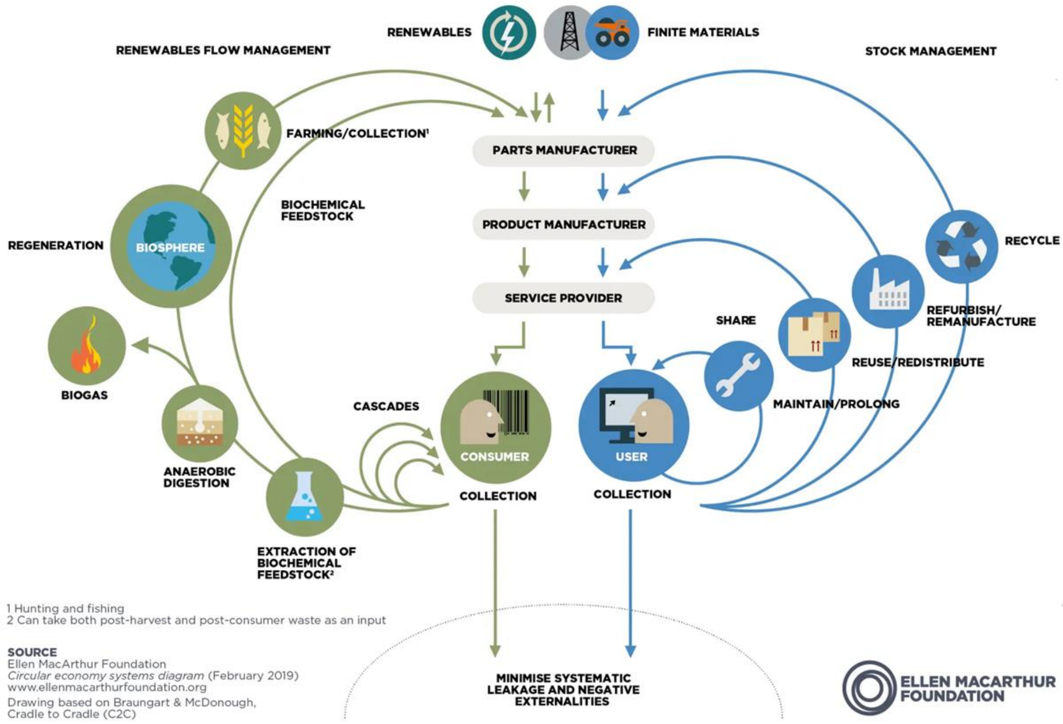

Figure 5 Butterfly diagram by EMF regarding processes for circular economy (Ellen MacArthur Foundation, 2022)

5.2 Results

5.2.1 Bibliometric analysis

The Table 9 shows the evolution of the number of publications on CIs in the buildings sector over the last decade. The increase in articles is particularly visible from 2020 onwards, which can be attributed to global efforts towards a more circular economy. The European Green Deal was launched in 2019, while the new Circular Economy Action Plan was adopted by the European Commission in 2020 (European Commission, n.d.). In terms of regions, Europe dominates, accounting for approximately three-quarters of the publication. Approximately 22% of these publications acknowledge funding from EU-funded projects, underscoring the significant role of EU initiatives in promoting research on circularity in the building sector. Notably, projects such as Drive 0[2] (EU Horizon 2020 Innovation Action) and CircularB[3] (COST Action) have supported the highest number of publications in this area. Taking into account the European research projects presented in **Fehler! Verweisquelle konnte nicht gefunden**

[2] DRIVE 0 - Driving decarbonization of the EU building stock by enhancing a consumer-centered and locally based circular renovation process funded by the European Union's Horizon 2020 Innovation action; https://www.drive0.eu/

[3] COST Action CA21103- Implementation of Circular Economy in the Built Environment (CircularB); https://circularb.eu/

werden., only Drive 0 and BAMB[4] were also indicated as a funding sources for the publications gathered through SLR identifying importance of assessing the scientific publications.

Table 9 Annual trend and geographical distribution of the publications

Annual trends											
Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
No. of publications	0	0	2	2	0	2	5	9	15	17	13
Geographical distribution											
Region	Europe		Asia	North America			South America			Australia	
No. of publications	47		10	2			2			4	

5.2.2 Collected circularity indicators' characterisation

5.2.2.1 Categorisation of the collected circularity indicators

The CIs can be categorised according to their thematic focus, as shown in Table A1 of Annex A. Some of the indicators have been renamed where similar meanings are found in more than one publication. Most of the indicators are designed to assess specific thematic areas, such as waste management, while others are broader in scope and often use general circularity terminology in their names to emphasise a more comprehensive circularity assessment (e.g., Circularity index). Following nine categories have been identified based on thematic areas:

1. Material sources;
2. Practices of extending the life span;
3. Practices for more circular deconstruction;
4. Practices for more circular construction stage;
5. Practices for recovery at the end-of-life;
6. Waste management;
7. Water management;
8. Directly addressing environmental impact;
9. Complex indicators.

5.2.2.2 Circular economy processes

With regard to the EMF butterfly diagram, the definitions of each of the processes for both technical and biological cycles are provided in Table 10. Those indicators that could not be correlated with any of the EMF cycle concepts were excluded from further consideration. It is important to distinguish between the terms "product" and "component" introduced at the beginning of the Section 5 and once in Table 10 by EMF. The "component" in Table 10 refers to ingredients that a "product" is made of. At this stage, the categorisation defined in Section 5.2.2.1 is used, with a focus on the representative indicators for each thematic area. This

[4] BAMB – Buildings as Material Banks: Integrating Materials Passports with Reversible Building Design to Optimise Circular Industrial Value Chains funded by the European Union's Horizon 2020 Innovation action; https://www.bamb2020.eu/

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approach aims to encompass as comprehensively as possible the circular processes that occur during the building life cycle.

Table 10 Description of EMF butterfly diagram processes (Ellen MacArthur Foundation, 2022)

Process	Definition
Technical cycle is a representative for finite products life cycle.	
Sharing	Operation to increase the intensity of product use.
Maintaining	Operation to maximise the value of a product by prolonging its usable life.
Reusing	Operation based on the repeated use of a product or component for its intended purpose without significant modification.
Redistributing	Operation of diverting a product from its intended market to another customer so it is used at high value instead of becoming waste.
Refurbishing	Operation that includes repairing or replacing components, updating specifications, and improving cosmetic appearance.
Remanufacturing	Operation involves re-engineering products and components to as-new condition with the same, or improved, level of performance as a newly manufactured one.
Recycling	Operation of transforming a product or component into its basic materials or substances and reprocessing them into new materials.
Biological cycle is representative of processes that return nutrients to the soil and help regenerate nature.	
Regeneration	Operation based on building natural capital covering practices that allow nature to rebuild soil and increase biodiversity.
Farming /collection	Operation based on collection of the nutrients in organic waste streams for returning to soil.
Composting and anaerobic digestion (biodegradability)	Composting refers to microbial breakdown of organic matter in presence of oxygen. Anaerobic digestion process that involves microorganism for recovering the materials embedded in organic waste in the absence of oxygen.
Cascading	Operation of loops utilising the biological cycle to make use of products and materials already in economy.
Extraction of biochemical feedstock	Operation of taking both post-harvest and post-consumer biological materials as feedstock, this step involves the use of biorefineries to produce low volume but high value chemical products.

5.2.2.2.1 Material sources

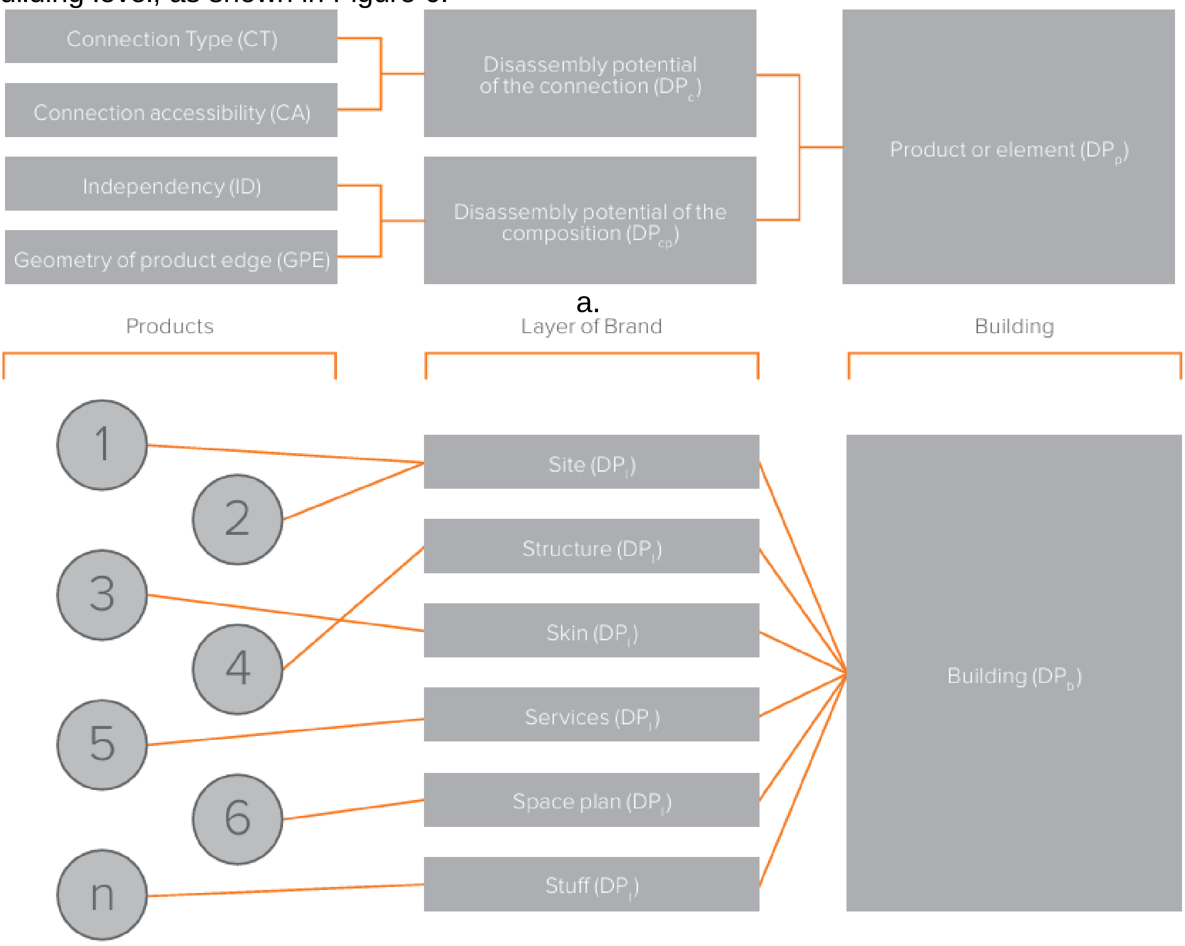
With regard to the CIs associated with this thematic area, two distinct categories can be identified, contingent on the number of processes under consideration. The first type comprises up to two processes, which are typically recycling and reuse. The second type encompasses a set of processes (e.g., Material input source (Göswein et al., 2022)). The **Material input source**, which estimates the percentage of material input sources of the product or of its components in terms of reused, recycled, biomass, or virgin material (Göswein et al., 2022), could be employed as a foundation for transparent CI regarding the source of the raw materials utilized.

5.2.2.2.2 Practices for extending the life span

In relation to this thematic area, the CIs are concerned with the evaluation of available measures for the purposes of adaptability, conservation, compatibility, durability, flexibility, maintenance and multifunctionality. These indicators primarily align with the maintaining process of the EMF butterfly diagram, while also sharing could be correlated with the CIs focused on flexibility, multifunctionality and durability. Reusing is addressed in the indicators directly associated with the adaptive reuse of a building, which is mainly investigated in the case of heritage buildings (Cucco et al., 2023; Pinto et al., 2023). The most circular processes are addressed by the **Longevity indicator**, which is based on a time (unit: months) that a resource is kept in use, considering initial lifetime, earned refurbished and recycled lifetime (Barrak et al., 2024). Such an indicator can encompass numerous practices of extending the life span if correctly defined.

5.2.2.2.3 Practices for more circular deconstruction

One of the principal areas of focus within the context of CIs pertaining to this thematic domain is the potential for disassembly, which typically includes the characterisation of connectors, functional dependence and geometrical features. The advantages of deconstruction result in the incorporation of a range of circular economy principles, contingent on the ultimate destination of the products or components following deconstruction. However, effectiveness of the deconstruction is vital, for which an **Effectiveness of the deconstruction process** indicator was proposed by (Jiménez-Rivero and García-Navarro, 2016) in their study on the end-of-life management of the gypsum. Nevertheless, the **Design for disassembly** assessment methods are most prevalent, which were pioneered by (Durmisevic, 2006), with one of the latest and most widely adopted updates by (van Vliet et al., 2021). The method by (van Vliet et al., 2021) is based on a scoring system and considers product, element and building level, as shown in Figure 6.



b.

Figure 6 Assessment of the disassembly potential of a. product or element and b. building (van Vliet et al., 2021)

5.2.2.2.4 Practices for more circular construction stage

In consideration of the construction phase, the practices for achieving circularity are closely related with resources management including energy, raw materials and land. **Circularity indicator for construction phase** applied in (Heisel and Rau-Oberhuber, 2020), addressed the utilisation of raw materials. The ratio of virgin materials to recycled, reused, or rapidly renewable materials is calculated. Consequently, it encompasses a multitude of circular processes, including both technical and biological cycles. Moreover, the **Land balance indicator** proposed by (Fagone et al., 2023) assesses excavated soil as a resource at the site and its reusing onsite instead of landfilling. Conversely, the CIs correlated with land use primarily concentrate on the conscious utilisation of land for construction, thereby avoiding the additional occupation of land. Two CIs, namely **Previously occupied land** and **Contaminated land** from (Fagone et al., 2023), concentrate on encouraging the use of land that has already been occupied by a building or fixed surface infrastructure. This is achieved by addressing the processes of sharing, maintaining and reusing. **Renewable energy** (Fagone et al., 2023) as the indicator on the other hand looks at the percentage of renewable energy of the total energy consumption, addressing mainly the cascading process in the biological cycle.

5.2.2.2.5 Practices for recovery at the end-of-life

Majority of the CIs regarding this thematic area focus on a single process from EMF's butterfly diagram, typically recycling or reusing. Three CIs focus on a larger number of circular economy processes, namely **Circularity indicator for end-of-life phase** (Heisel and Rau-Oberhuber, 2020), **Material recovery potential index** (Mayer and Bechthold, 2017) and **Recovery rate** (Saadé et al., 2022).

5.2.2.2.6 Waste management

With regard to the CIs pertaining to waste management, two distinct groups can be identified. The first group encompasses those that focus on the spectrum of waste management actions, while the second group is characterised by a narrower focus on a single action. The former category includes **Waste scenarios** (Göswein et al., 2022), **Waste diversion rate** (Ratnasabapathy et al., 2020) and **Reduce CDW to landfill through recovery and reuse on or off-site** (Foster et al., 2020), which collectively represent a comprehensive range of waste management strategies. Hence addressing the processes of the EMF butterfly diagram associate with the avoidance of waste landfilled (e.g., reusing, recycling, redistributing, etc.).

5.2.2.2.7 Water management

The CIs associated with water management typically focus on the water circulation capacity either through specific measures such as Stormwater runoff management in the site (Stracqualursi and Andreucci, 2024) or more generic **Water circularity** indicators (Fagone et al., 2023; González et al., 2021). With regard to the EMF's butterfly diagram processes, there is no significant distinction between the indicators due to their general focus on the utilisation of reused water sources; however, the CIs with the most comprehensive evaluation are essential.

5.2.2.2.8 Directly addressing environmental impact

The CIs that address the environmental impact directly tend to concentrate on GHG emissions, energy, natural resources and hazardous materials. The majority of these indicators are correlated with the specific EMF's butterfly diagram process, without looking at a wholistic environmental impact. The **Generalised ecological indicator** (Sobierajewicz et al., 2023) is based on a methodology for assessing the cumulative ecological, economic and technical parameters for the assessment of ecological effect of a steel halls. However, it has only been applied in the context of a reuse case. On the other hand, **Retained environmental value**

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(Barrak et al., 2024) is defined as the quantification of the original environmental impact that can be retained in the technosphere through the implementation of value retention processes (e.g., reuse, remanufacturing, recycling, etc.) (Haupt and Hellweg, 2019). Consequently, this CI is contingent upon the end-of-life processes and is therefore applicable to a diverse range of circular economy processes.

5.2.2.2.9 Complex indicators

Although there is a considerable range of CIs within this category, it is notable that the approach of adopting the EMF's **Material circularity indicator** and using it as a foundation for **Product, System and Building circularity indicator** is the most prevalent (Gomes et al., 2022; Shin and Kim, 2024). This methodology also aligns directly with the EMF's butterfly diagram in a comprehensive manner.

5.2.2.3 Indicator type and material balance

Based on the previous steps assessing the CIs based on the thematic areas (Section 5.2.2.1) and circular economy processes (Section 5.2.2.2), the CIs outlined in Table 11 are further evaluated. While some indicators, such as Design for Disassembly, employ a scoring system that could be perceived as semi-quantitative, the scoring is primarily based on technical characteristics, thereby reducing subjectivity. Consequently, all of the aforementioned CIs are classified as quantitative. Moreover, the majority of CIs are based on material balance, with the exception of those specifically pertaining to disassembly processes or land use for construction. For the Material, Product, System, and Building circularity indicators, from this point forward, only references that comprehensively address all scales—from material to building—are used (i.e., (Gomes et al., 2022; Shin and Kim, 2024)) int the complex indicators category, as these support a complete approach.

Table 11 Circularity indicators assessment based on their type and if they are based on material flow analysis or not

Thematic area	Circularity indicator (reference)	Indicator type	Material balance based
Material sources	Material input source (Göswein et al., 2022)	Quantitative	Yes
Practices for extending the life span	Longevity indicator (Barrak et al., 2024)	Quantitative	Yes
Practices for more circular deconstruction	Effectiveness of the deconstruction process (Jiménez-Rivero and García-Navarro, 2016)	Qualitative	Yes
	Design for disassembly (Bitar et al., 2022)	Quantitative	No
Practices for more circular construction stage	Circularity indicator for construction phase (Heisel and Rau-Oberhuber, 2020)	Quantitative	Yes
	Land balance indicator (Fagone et al., 2023)	Quantitative	Yes
	Previously occupied land (Fagone et al., 2023)	Quantitative	No
	Contaminated land (Fagone et al., 2023)	Quantitative	No

Thematic area	Circularity indicator (reference)	Indicator type	Material balance based
Practices for recovery at the end-of-life	Circularity indicator for end-of-life phase (Heisel and Rau-Oberhuber, 2020)	Quantitative	Yes
	Material recovery potential index (Mayer and Bechthold, 2017)	Quantitative	Yes
	Recovery rate (Saadé et al., 2022)	Quantitative	Yes
Waste management	Waste scenarios (Göswein et al., 2022)	Quantitative	Yes
	Waste diversion rate (Ratnasabapathy et al., 2020)	Quantitative	Yes
	Reduce CDW to landfill through recovery and reuse on or off-site (Foster et al., 2020)	Quantitative	Yes
Water management	Water circularity (Fagone et al., 2023; González et al., 2021)	Quantitative	Yes
Directly addressing environmental impact	Retained environmental value (Barrak et al., 2024)	Quantitative	Yes
Complex indicators	Material circularity indicator (Gomes et al., 2022; Shin and Kim, 2024)	Quantitative	Yes
	Product circularity indicator (Gomes et al., 2022; Shin and Kim, 2024)	Quantitative	Yes
	System circularity indicator (Gomes et al., 2022; Shin and Kim, 2024)	Quantitative	Yes
	Building circularity indicator (Gomes et al., 2022; Shin and Kim, 2024)	Quantitative	Yes

5.2.2.4 Scales of building composition and conformity to LCA modules

In this section the CIs selected will be discussed in detail looking into their definitions and methodologies as well as applicability to modules of LCA (Figure 4), excluding module D. In Table 12 the short-listed CIs are characterised based on the modules that they can address and the scales of building composition to which they can be applied.

Table 12 Circularity indicators conformity to LCA modules and scales of building composition to which they can be applied

Circularity indicator	LCA module	Product	Component	Building
Material input source	A1-3, B3-5	X	X	X

Circularity indicator	LCA module	Product	Component	Building
Longevity indicator	A, B, C	X	X	
Effectiveness of the deconstruction process	B3-5, C	X	X	X
Design for disassembly	A4-5, B3-5, C		X	X
Circular indicator for construction phase	A4-5	X	X	X
Land balance indicator	A4-5			X
Previously occupied land	A4-5			X
Contaminated land	A4-5			X
Circular indicator for end-of-life phase	B3-5, C	X	X	X
Material recovery potential index	A, B3-5, C	X	X	
Recovery rate	A4-5, B3-5, C	X	X	X
Waste scenarios	A4-5, B3-5, C	X	X	X
Waste diversion rate	A4-5, B3-5, C	X	X	X
Reduce CDW to landfill through recovery and reuse on or off-site	A4-5, B3-5, C	X	X	X
Water circularity	A, B, C	X	X	X
Retained environmental value	A, B, C	X	X	X
Material-Product-Building circularity indicator	A, B, C	X	X	X

5.2.2.4.1 Material input source

This CI is based on the percentage of the resources type either as reused, recycled, biomass or virgin (Göswein et al., 2022). While the materials input is typically associated with module A1-3 of the LCA methodology, during the use stage, due to repair, refurbishment or replacement (i.e. B3-5), there is an inflow of materials which could be assessed also using this indicator. With regard to the methodology for presenting the results of the indicator, it is recommended that the ratio between the total weight/volume of resources used by specific source type (i.e., reused, recycled, bio-based and virgin) would be presented. As material flow can be followed throughout the whole lifetime of the building, this indicator can easily be adopted to each building scale.

5.2.2.4.2 Longevity indicator

(Barrak et al., 2024) adopted this CI from a study by (Franklin-Johnson et al., 2016), where Longevity indicator is calculated as a sum of initial lifetime of the product, refurbished and recycled lifetime contribution using the following equations:

$$Longevity = A + B + C\ [months] \tag{1}$$

Where,
A – initial lifetime of the product;
B – refurbished lifetime;
C – recycled lifetime.

The detailed explanation of the methodology for this CI is given in (Franklin-Johnson et al., 2016). Nevertheless, it encompasses all three modules of the LCA methodology (namely module A-C). With respect to scale of building composition, this indicator can be easily adopted to product and component scale, while on a building scale the approach should be modified.

5.2.2.4.3 Effectiveness of the deconstruction process

This CIs was applied by (Jiménez-Rivero and García-Navarro, 2016) through an assessment of the presence of wet gypsum waste and impurities, with the objective of developing an effective recycling process for the gypsum. It was therefore proposed that two sub-indicators be established, namely "Impurities" and "Gypsum waste accepted." The Impurities indicator was a qualitative measure based on the visual examination of contaminants in the gypsum waste upon delivery to the recycling facility. Conversely, the Gypsum waste accepted indicator was a quantitative measure that evaluated the discrepancy between the recyclable gypsum waste that was rejected by the recycling facility and the recyclable waste that was sent to it.

Consequently, this CI primarily assesses module C of the LCA methodology, incorporating both deconstruction and waste processing. As a consequence of the repair, refurbishment and replacement stages inherent to module B, which also generate deconstruction waste, this CI is pertinent to modules B3-5 as well. When upscaled to encompass deconstruction waste in general, the Waste accepted sub-indicator could be employed in a comprehensive manner, thereby addressing both recycling and reusing. In this case, the Effectiveness of the deconstruction process indicator would be based on the deconstruction waste sent to waste processing facilities and the total waste recovered. The indicator could be correlated with the life cycle of a specific building product, component, or building at the end-of-life.

5.2.2.4.4 Design for disassembly

The methodology for Design for disassembly indicator was based on Alba Concepts (van Vliet et al., 2021), which focused on four aspects of the connections: connection type, accessibility, piercing and inclusion (Bitar et al., 2022). The methodology employs a scoring system on a scale of 0 to 1, with 0.1 and 1.0 representing the minimum (i.e., least favourable) and maximum (i.e., more favourable) values, respectively. The basis of the scoring can be found in Table 3 of a study by (Bitar et al., 2022). The average of the scores on each aspect correspond to the value of the Design for disassembly indicator. In the case of a building comprising a number of construction elements, a weighted average is recommended. This CI is correlated with the construction and demolition modules of the LCA methodology, as well as the repair, refurbishment and replacement stages of the use module, given that specific components might be disassembled.

5.2.2.4.5 Circularity indicator for construction phase

This CI is associated with the raw materials employed during the construction phase, representing the proportion of recycled (F_R), rapidly renewable (F_{RR}) and reused (F_U) materials (Heisel and Rau-Oberhuber, 2020). Similarly to the Material Input Source Indicator, this indicator can be readily implemented at all scales of building composition. However, due to its particular focus on the materials utilised during the construction phase, it is only pertinent to module A4-5.

$$CI_{construction} = F_R + F_{RR} + F_U \ [\%\ of\ total\ mass] \tag{2}$$

5.2.2.4.6 Land balance indicator

This CI is specifically assessing the reuse of the excavated soil on site using the following formula (Fagone et al., 2023):

$$Land\ balance\ indicator = {}^{Vtr_{tot}}/_{Vs_{tot}} \times 100\ [\%] \tag{3}$$

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Where,
Vtr_{tot} – total volume of waste soil reused on site;
Vs_{tot} – total volume of excavations.
As this indicator is focused specifically on the excavated soil during the construction of the building, it can be applied only at the building scale and to module A4-5.

5.2.2.4.7 Previously occupied land

This indicator is concerned with the footprint of the new development and whether the area in question has previously been occupied by industrial, commercial, domestic buildings or fixed surface infrastructure (Fagone et al., 2023). Mainly if the area of application has been previously "contaminated" by manmade (infra)structure. So it is based on a ratio calculation regarding the footprint. In a manner analogous to the preceding indicator (i.e., Land balance indicator), this CI can be applied at the building scale and module A4-5.

5.2.2.4.8 Contaminated land

The formula for calculating the Contaminated land indicator takes into account the following parameters (Fagone et al., 2023):

$$Contaminated\ land = \frac{Bi}{A} \times (-1) + \frac{Bii}{A} \times (0) + \frac{Biii}{A} \times (3) + \frac{Biv}{A} \times (5)\ [-] \tag{4}$$

Where,
A – site area;
Bi – area of the site with soil characteristics in their natural state;
Bii – area of site with green areas and/or on which there were agricultural activities;
Biii – area of site on which there were building structures or infrastructures;
Biv – area of site on which remediation operations were conducted (or planned).
This CI is applicable only to building scale and module A4-5.

5.2.2.4.9 Circularity indicator for end-of-life phase

This CI is based on the ratio of the materials that can be potentially recycled (C_R) and reused (C_U) at the end-of-life taking into account also the efficiency of the recycling process (E_c) (Heisel and Rau-Oberhuber, 2020):

$$Circularity\ indicator\ for\ end-of-life\ phase = C_R \times E_C + C_U\ [\%] \tag{5}$$

However, in order for products and/or components to be considered reusable or recyclable, certain conditions must be met. These specifications are presented in (Heisel and Rau-Oberhuber, 2020), but are, in general, based on disassembly options. As indicated by the indicator's designation, it can be applied to module C, as previously stated, and also to modules B3-5 due to repair, refurbishment, and replacement. With regard to the various levels of construction, the indicator may be applied to products, components and buildings.

5.2.2.4.10 Material recovery potential index

As proposed by (Mayer and Bechthold, 2017), the indicator is applicable to products and assemblies and is based on a score between 0-1, with higher scores being more favourable. It is based on multi-criteria decision analysis, which assigns weights to different (sub)criteria of the indicator (Figure 7). The analytical hierarchy process is one of the most commonly used and is based on a comparative ranking of indicators. Based on the interviews with the industry expert, weightings are assigned to each criteria of the indicator and formulas are proposed for the calculation of both the product and the assembly (component in this study) as shown in Eq. 6 and 7 (Mayer and Bechthold, 2017). A detailed explanation of the equation variables can be found in (Mayer and Bechthold, 2017) As the referenced study specifically assigns indicators to the product and component scales, it is clear to which scale of building composition the indicator is applied. Furthermore, with regard to the modules considered, in the case of the product, both module A1-3 and module C are addressed. In the case of the assembly scale (i.e. module A4-5), modules B4-5 and C1 are also included.

$$MRPI_{Product} = 0.3 \times MRP_{Re(\$)} + 0.3 \times MRP_{Re(CO2)} + 0.1 \times MRP_{Surface} + 0.25 \times MRP_{Binders} + 0.05 \times (1 - MRP_{Diversity})\ [-] \quad (6)$$

Where,
$MRP_{Re(\$)}$ – recyclability market value index;
$MRP_{Re(CO2)}$ - recyclability CO_2 index;
$MRP_{Surface}$ – surface treatment index;
$MRP_{Binders}$ – binders index;
$MRP_{Diversity}$ – material diversity score.

$$MRPI_{Assembly} = 0.3 \times AVRG_{Products} + 0.4 \times MRP_{Connection} + 0.2 \times MRP_{Access} + 0.1 \times MRP_{Integration}\ [-] \quad (7)$$

Where,
$AVRG_{Products}$ – product scores factored into the assembly index;
$MRP_{Connection}$ – connection type index;
MRP_{Access} – access index;
$MRP_{Integration}$ – component integration index.

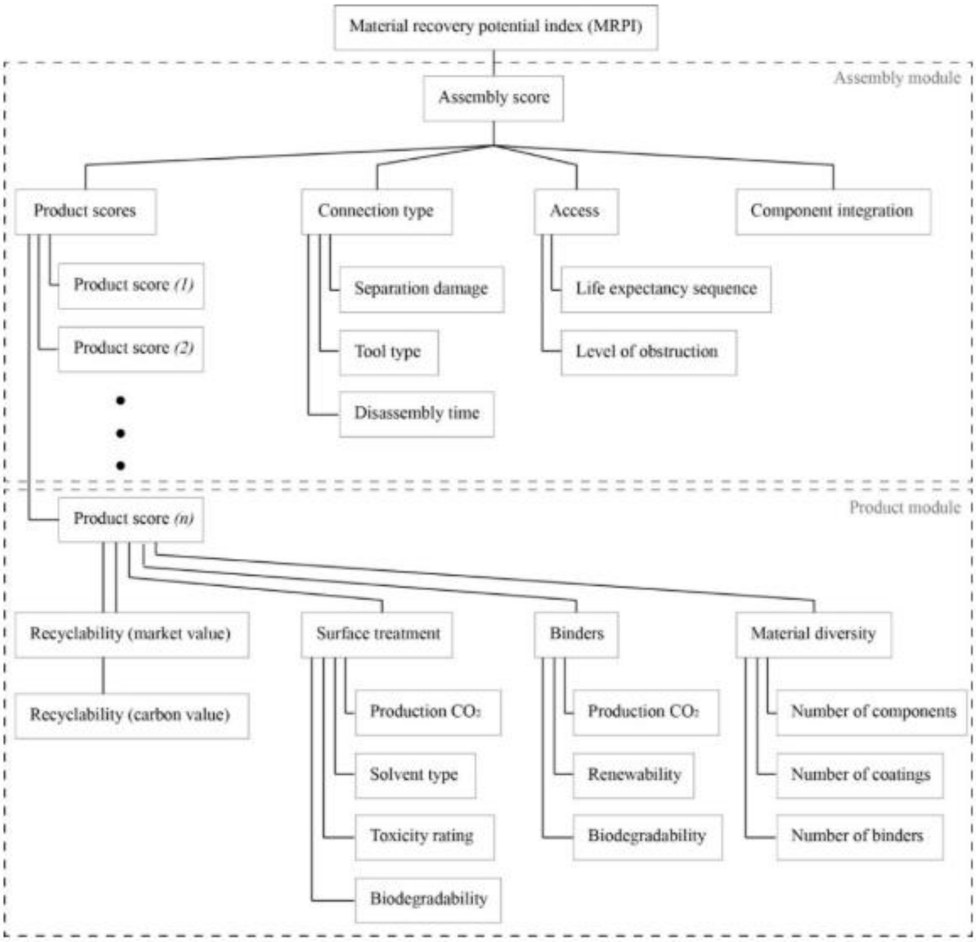

Figure 7 Material recovery potential index assessment framework (Mayer and Bechthold, 2017)

5.2.2.4.11 Recovery rate

This CI examines the recovery of secondary materials and waste at the urban project's end-of-life (Saadé et al., 2022). However, during the construction, use and end-of-life phases, waste is generated depending on the amount of site activities carried out during the whole life cycle of the building. (Saadé et al., 2022) applied this indicator in relation to the type of materials used, such as metals, minerals, hardwood, softwood, plastics, insulation, etc. Such an approach would require effective traceability of the material flow throughout the life cycle of the building. However, looking more at a product-based recovery rate, as provided on the site, could provide a more transparent insight into the management of waste. Therefore, if properly defined, it could be an essential CI that could be applied at the building scale and a variety of LCA modules (i.e. A4-5, B3-5 and C).

5.2.2.4.12 Waste scenarios

The CI proposed by (Göswein et al., 2022) quantifies the amount of waste sent to reuse, recycling, energy recovery, backfilling or other and landfill scenarios. Similarly to previous CIs (i.e., Recovery rate), it can be applied at all scales of building composition and to modules whose activities produce waste (i.e., A4-5, B3-5, C).

5.2.2.4.13 Waste diversion rate

This CI is defined as the ratio of waste that has been diverted from landfill through the utilisation of a variety of scenarios, including reuse, recycling, repair, treatment and energy recovery (Ratnasabapathy et al., 2020). Although (Ratnasabapathy et al., 2020) specifically applied the indicator to the construction stage and only recycling and energy recovery were considered as scenarios for waste diversion (see Eq. 8), the comprehensiveness of the indicator can be improved. In addition to the construction stage module, B3-5 and C could be evaluated in accordance with the aforementioned waste management indicators. Furthermore, in addition to recycling and energy recovery as waste diversion options, other favourable waste scenarios such as reuse could be incorporated. Overall, the applicability of the indicator can be relevant for all scales of building composition.

$$WDR = \frac{Total\ waste\ diverted}{Total\ waste\ generated} \times 100$$
$$= \frac{Recycling + Energy\ recovery}{Recycling + Treatment + Energy\ recovery + Landfill + Other\ disposal} \times 100\ [\%] \qquad (8)$$

5.2.2.4.14 Reduce CDW to landfill through recovery and reuse on or off-site

The CI defines the reduction in CDW through recovery and reuse on or off-site, expressed in tons of cubic metres (Foster et al., 2020). The three CIs associated with the waste management thematic area are unified in their objective of reducing the amount of waste landfilled. Therefore, a comprehensive indicator could address all three areas presented in Waste scenarios, Waste diversion rate and Reduce CDW to landfill through recovery and reuse on or off-site indicators. The relevant assessment regarding the scales of building composition and modules that could be addressed through this CI is consistent with the preceding two indicators (i.e, Section 5.2.2.4.12 and 5.2.2.4.13).

5.2.2.4.15 Water circularity

The indicator presented by (Fagone et al., 2023) (based on the Circular transition indicator by the World Business Council of Sustainable Development (World Business Council of Sustainable Development, n.d.)) is a ratio of circular water inflows and outflows as shown in Eq. 9. On the other hand, (González et al., 2021) proposed a comprehensive Water circularity indicator, which is a ratio of circular and on-site water to total water used (Eq. 12). Therefore, the calculation method proposed by (González et al., 2021) includes all LCA modules and addresses all scales of building composition.

$$Water\ circularity = \frac{Circular\ water\ inflow + Circular\ water\ outflow}{2} \times 100[\%] \qquad (9)$$

Where,

$$Circular\ water\ inflow = \frac{Total\ circular\ water\ withdrawal}{Total\ water\ withdrawal} \times 100\ [\%] \qquad (10)$$

$$Circular\ water\ outflow = \frac{Total\ circular\ water\ discharge}{Total\ water\ withdrawal} \times 100\ [\%] \qquad (11)$$

$$Water\ circularity\ indicator = \frac{CW_{A1-3} + CW_{A4-5} + CW_B + CW_C}{W_{A1-3} + W_{A4-5} + CW_B + W_C}\ [\%] \qquad (12)$$

Where the subscripts of the variables correspond to the LCA modules, *CW* is the recycled water from various water reutilisation or wastewater sources (i.e., grey water, black water, rain water) and *W* stands for total water use. Unit for both *CW* and *W* is cubic meters.

5.2.2.4.16 Retained environmental value

The CI is adopted from a study of (Haupt and Hellweg, 2019) by (Barrak et al., 2024) and is calculated by comparing the environmental impact of the displaced product or material (EI_{disp}) after accounting for the impact of the value retention process (EI_{vrp}) relative to the original product's impact ($EI_{original}$). The differences in environmental impacts during the use-phase can be also considered in the equation (Eq. 13) using $EI_{surplus}$ variable which accounts for changed efficiency of a retained and alternative primary product. If a product consists of more than one material, the environmental impacts can be summed up according to the following formula:

$$Retained\ envrionmental\ value = \frac{\sum_{j=1}^{n}\left(EI_{disp,j} - EI_{vrp,j}\right) - EI_{surplus}}{\sum_{i=1}^{n}\left(EI_{original,i}\right)}\ [-] \qquad (13)$$

The CI can be applied to all scales of building composition and LCA modules, as environmental impacts are present throughout the entire building life cycle.

5.2.2.4.17 Material-Product-Building circularity indicator

The four indicators from Section 5.2.2.2.9 were consolidated into a single CI due to their interconnectivity. The methodology for determining the Building circularity indicator (Figure 8) commences with the calculation of the Material circularity indicator (Eq. 14, which is based on an approach proposed by EMF (Gomes et al., 2022; Shin and Kim, 2024).

$$Material\ circularity\ indicator = \max\left(0{,}1 - \frac{0.9}{X} LFI\right)\ [-] \qquad (14)$$

Where,

LFI – linear flow index, is a measure of the proportion of material sourced from virgin materials that ends up as unrecoverable waste;

X – utility factor accounts for the product's lifetime and intensity of use.

A comprehensive description of the Material circularity indicator, along with the associated calculation procedure, can be found in (Goddin et al., 2019). While some studies have modified the equations used for the building sector, the core framework is largely based

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on this approach.

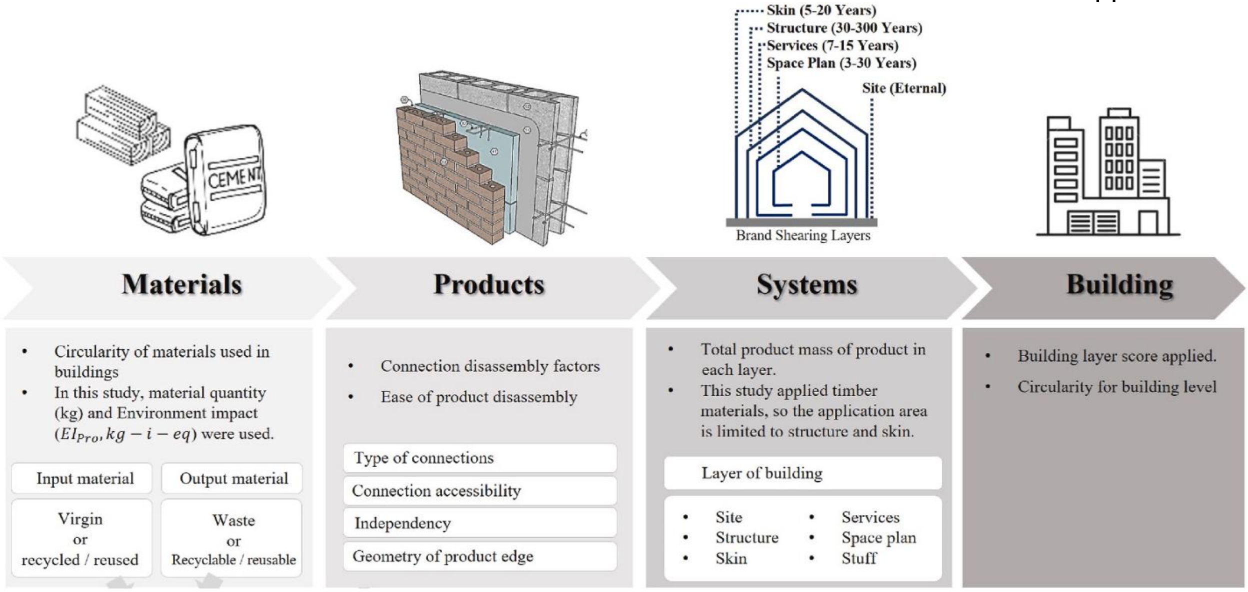

Figure 8 Building circularity indicator framework (Shin and Kim, 2024)

The second step of the methodology is typically Product circularity indicator, which accounts for the connection and disassembly (Eq. 15). Hence, based on the terminology used in this study, the Material circularity indicator is correlated with the product, while Product circularity indicator is correlated with the component.

$$Product\ circularity\ indicator = Material\ circularity\ indicator \times \frac{1}{F_d}\sum_{i=1}^{n} F_i\ [-] \qquad (15)$$

Where,
F_d – number of design criteria, which in the case of study by (Shin and Kim, 2024) is type of connections, connection accessibility, independency and geometry of product edge;
F_i - scores assigned for each design criteria (Figure A1 in Annex A).

Given the disparate lifespans of the various building layers, a System circularity indicator is proposed. Typically, layers are defined in accordance with the classification proposed by (Brand, 1994) as shown in Figure 8, with corresponding lifespan estimates. Consequently, the System circularity indicator builds upon the Material and Product circularity indicators as shown in Eq. 16.

$$System\ circularity\ indicator = \frac{1}{M_s}\sum_{j=1}^{J_s} M_j \times Product\ circularity\ indicator_j\ [-] \qquad (16)$$

Where,
M_s – total mass of a product *j* in layer *s*;
J_s – total number of products in the layer *s*;
M_j – amount of product *j*.

Ultimately, the Building circularity indicator synthesises the preceding indicators into a comprehensive score (Eq. 17), considering the building layer score in accordance with its relative importance (*LK*). While there are various methodologies for calculating the Building circularity indicators, they are primarily based on the same principles of assigning scores to the four levels. The equations presented in this section (Eq. 14-17) are derived from those in (Shin and Kim, 2024). However, for variations of the equations based on specific criteria, please refer to the references provided in Table A1 in Annex A.

$$Building\ circularity\ indicator = \frac{1}{LK}\sum_{s=1}^{S} LK_s \times System\ circularity\ indicator_s\ [-] \qquad (17)$$

Where,
LK – sum of all the level of importances scores (see Table 1 in (Gomes et al., 2022));
S – total number of layers.

Accordingly, at each stage of the Building circularity indicator, either a product, component, or a building is addressed, with the exception of the System circularity, which can be regarded as an intermediate step for the final Building circularity indicator calculation. Hence, in Table 12, only one indicator will be introduced as the Material-Product-Building Circularity Indicator. Considering the material input, end-of-life, (dis)assembly, and lifespan, it can be concluded that all LCA modules are included.

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Conclusion

By structuring the approach for assessing circularity within the BIO4EEB project into four main stages—setting precise objectives and action plan, conducting a literature review on circularity analysis, developing a circular referential analysis, and creating a certification scheme—this framework provides a comprehensive way to evaluate and enhance the circularity of construction products and buildings.

The initial phase of setting objectives enabled to align the scope of the study with the broader goals of the BIO4EEB project and to ensure that all involved partners had a clear understanding of the input data requirements and expected outcomes. The literature review offered valuable insights into existing circularity indicators and methodologies used in European projects, standardization works, and scientific research, ensuring that the methodology is grounded in current best practices. The circular referential analysis stage provided a detailed selection of the most relevant parameters for assessing circularity.

Finally, the creation of a certification scheme represents a critical stage in operationalizing the methodology and will be achieved over the next two years. By carefully selecting and defining appropriate indicators, the project will establish a clear and practical approach to measure and improve circularity. This scheme will allow for the consistent and transparent assessment of BIO4EEB solutions and demo-cases.

Overall, the methodology described in this document is intended to be a valuable tool for advancing the principles of circularity in the construction industry.

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Annex A

Characterisation of the circularity indicators

Table A1 Categorisation of circularity indicators

Thematic area	Indicator for product scale (reference)	Indicator for component scale (reference)	Indicator for building scale (reference)
Material sources	Material input source (Göswein et al., 2022)	Recycled materials (Finch et al., 2021; Fregonara et al., 2017) Materials indicator (Daly, 2023) Material input source (Göswein et al., 2022)	Level of use of reusable and recycled materials (Calvo-Serrano et al., 2020) Materials/components issued from the reuse (Bendahmane et al., 2022; Nocca and Angrisano, 2022) Recovered content (Luciano et al., 2023; Saadé et al., 2022) Disassembly material (Fagone et al., 2023; Luciano et al., 2023) Material from renewable sources (Fagone et al., 2023) Recycled materials (Fagone et al., 2023; Luciano et al., 2023; Trubina et al., 2024) Amount of secondary material; Demand for renewable material (Munaro and John, 2024) Traditional and/or biomass and/or local sustainable materials (Foster et al., 2020)

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Practices for extending the life span	Information exchange system; Reusability; Safe management; Track maintenance; (Zhuang et al., 2023);	Flexibility and multifunctionality (Masseck et al., 2024) Joints and materials withstand repeated use (durability) (Finch et al., 2021) Information exchange system; Safe management; Track maintenance; (Zhuang et al., 2023) Longevity indicator; (Barrak et al., 2024) Reusability (Antwi-Afari et al., 2023a; Masseck et al., 2024; Zhuang et al., 2023)	Flexibility score (Geraedts, 2016) Circularity indicator for use phase (Heisel and Rau-Oberhuber, 2020) Conservation of the geometric features; Overall state of preservation of the building; Recognisability and acceptability of the transformations; Reuse of buildings: retaining existing technical elements and finishes Reversibility of conservation action; Scale & severity of change/impact; Significance of effect or overall impact (Nocca and Angrisano, 2022) Conservation of technic elements; Life-long transformation; Preservation of aesthetic relationship with the context; Preservation of the existing building dimension; Respect for the construction system (Pinto et al., 2023) Compatibility (of transformation) (Cucco et al., 2023; Pinto et al., 2023) Proportionality (Cucco et al., 2023) Sustainability (Cucco et al., 2023; Zhuang et al., 2023) Extending the life of the building with a focus on functional adaptability

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			(Trubina et al., 2024) Level of reusable waste; (Calvo-Serrano et al., 2020) Reusability/reused CDW (Al-Obaidy et al., 2022; Mercader-Moyano et al., 2022) Reuse materials and objects onsite; Reuse materials and objects offsite (Foster et al., 2020) Enabling future reuse of building elements and materials; (Trubina et al., 2024)
Practices for more circular deconstruction	-	Level of disassembly (Fregonara et al., 2017) Assembly direction; Base element specification; Relational pattern; Standardisation of product edge; Structural and materials level (Androsevic et al., 2019) Functional (in)dependence; Type of connection (Androsevic et al., 2019; Daly, 2023) Disassembly instructions (Göswein et al., 2022) Adopt prefabrication; Components sized to suit the means of handling; Chemical material connections;	Effectiveness of audit for deconstruction; Effectiveness of the deconstruction process (Jiménez-Rivero and García-Navarro, 2016) Disassembly material (Fagone et al., 2023; Luciano et al., 2023)

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		Disassembly requires only common tools and equipment; Reversible mechanical connections; Quantity of connectors; Quantity of different types of connectors; Quantity of different types of materials; Structurally independent layers; Secondary finishers on materials (Finch et al., 2021) Design for disassembly (index) (Bergmans et al., 2023; Bitar et al., 2022; Göswein et al., 2022) Accessibility of connection; Type of product edge (Daly, 2023)	
Practices for more circular construction stage	-	-	Circularity indicator for construction phase (Heisel and Rau-Oberhuber, 2020) Contaminated land; Land balance indicator; Onsite water circularity; Previously occupied land; Renewable energy (Fagone et al., 2023) Increase land use efficiency due to adaptive reuse; Limit land use change; (Foster et al., 2020) Reduction of construction waste

			(Trubina et al., 2024)
Practices for recovery at the end-of-life	GHG emissions processing and transport; Output materials of the recycling process; Recycled product rejected; Recycled product quality criteria; Warehouse space; Waste rejected (for recovery) (Jiménez-Rivero and García-Navarro, 2016) Material recovery potential index (Mayer and Bechthold, 2017) Recyclable material; Recycling technology; Reusability (Zhuang et al., 2023)	Material recovery potential index (Mayer and Bechthold, 2017) High value recycling possible? (Finch et al., 2021) Recyclability/ recyclable material/ recycling rate (Barrak et al., 2024; Masseck et al., 2024; Roithner et al., 2022; Zhuang et al., 2023) Recycling technology (Zhuang et al., 2023) Reusability (Antwi-Afari et al., 2023a; Masseck et al., 2024; Zhuang et al., 2023)	Level of recycled waste; Level of reusable waste (Calvo-Serrano et al., 2020) Circularity indicator for end-of-life phase (Heisel and Rau-Oberhuber, 2020) Offsite recycled CDW; Onsite recycled CDW (Mercader-Moyano et al., 2022) Reusability/reused CDW (Al-Obaidy et al., 2022; Mercader-Moyano et al., 2022) Reuse materials and objects onsite; Reuse materials and objects offsite (Foster et al., 2020) Recovery rate (Saadé et al., 2022) Recyclability/recycling rate (Roithner et al., 2022; Saadé et al., 2022) Enabling future reuse of building elements and materials; Reduction of construction waste (Trubina et al., 2024)
Waste management	Amount sent to landfill; Transport of waste emissions comparison; Waste acceptance criteria; Effectiveness of the traceability (Jiménez-Rivero and García-Navarro, 2016)	Quantity of devalued materials (waste) after a use and deconstruction cycle (Finch et al., 2021)	Waste diversion rate (Ratnasabapathy et al., 2020) Land balance indicator (Fagone et al., 2023) Reduce C&D waste to landfill through recovery and reuse on or off-site (Foster et al., 2020)

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	Waste scenarios (Göswein et al., 2022) Storage circularity indicator (Pilipenets et al., 2024)		
Water management	-	-	Reducing external water use (Nocca and Angrisano, 2022) Onsite water circulation (Fagone et al., 2023; Foster et al., 2020) Water circularity (index) (Fagone et al., 2023; González et al., 2021) Effectiveness of water purification; Reuse potential of water resources; Stormwater runoff management in the site (Stracqualursi and Andreucci, 2024) Improve water quality measured as eutrophication potential based on nutrient loads; Increase water efficiency/freshwater consumption (Foster et al., 2020)
Directly addressing environmental impact	GHG emissions processing and transport (for end-of-life scenarios) Natural resource saved (by recovery of product at end-of-life) Transport of waste emissions comparison (for end-of-life scenarios)	Chemically hazardous materials (Finch et al., 2021) Generalised ecological indicator (Sobierajewicz et al., 2023) Renewable resources (Zhuang et al., 2023) Retained environmental value (Barrak et al., 2024)	Generalised ecological indicator (Sobierajewicz et al., 2023) Energy circularity index (González et al., 2021) Improve water quality measured as eutrophication potential based on nutrient loads; Increase water efficiency/freshwater consumption; Increase energy efficiency/consumption;

	(Jiménez-Rivero and García-Navarro, 2016) Renewable resources (Zhuang et al., 2023)		Increase amount of non-renewable vs. renewable energy use; Indirect emission reudctions due to the adaptive reuse; Maintain embodied energy in on site reused concrete, stone, brick, steel, etc.; Maintain embodied energy in off site reused concrete, stone, brick, steel, etc.; Provide habitat for specific endangered or culturally relevant species; (Foster et al., 2020) Reducing external water use; (Nocca and Angrisano, 2022) Renewable energy; (Nocca and Angrisano, 2022) Onsite water circulation; (Fagone et al., 2023; Foster et al., 2020) Water circularity (index) (Fagone et al., 2023; González et al., 2021) Effectiveness of water purification; Reuse potential of water resources; Stormwater runoff management in the site (Stracqualursi and Andreucci, 2024)
Complex indicators	Circularity index (Medina et al., 2021) Material circularity indicator (Dräger et al., 2022; Giama et al., 2019; Giama and Papadopoulos, 2020; Gomes et al., 2022; Jiang et	Circularity features (Kosanović et al., 2021) Product circularity indicator (Barrak et al., 2024; Cottafava and Ritzen, 2021; Gomes et al., 2022; Mazzoli et al., 2022; Shin and Kim, 2024)	3DR index (O'Grady et al., 2021) Circularity indicator for construction phase; Circularity indicator for use phase (Heisel and Rau-Oberhuber, 2020) "9R" strategy;

	al., 2022; Poolsawad et al., 2023; Saadé et al., 2022; Shin and Kim, 2024; Tanthanawiwat et al., 2024; van der Zwaag et al., 2023)	Circular economy indicator prototype; Circular economy performance indicator; Circularity index; Circularity index (Agrocirclewins); Material circularity indicator; Material reutilisation score (Barrak et al., 2024)	"Resolve" system (Dişli and Ankaralıgil, 2023) Circular economy principles (Munaro and John, 2024) Circularity index (Lei et al., 2022; Medina et al., 2021; Munaro and John, 2024) Material circularity (index) (Fagone et al., 2023; González et al., 2021) Circularity indicator building score (Medina et al., 2021) Building circularity indicator (Antwi-Afari et al., 2023b; P. Antwi-Afari et al., 2022; Prince Antwi-Afari et al., 2022; Braakman et al., 2021; Cottafava and Ritzen, 2021; Gomes et al., 2022; Jiang et al., 2022; Khadim et al., 2023; Mazzoli et al., 2022; Shin and Kim, 2024; van der Zwaag et al., 2023; Zhang et al., 2021) Building circularity score (Vilcekova et al., 2024; Vilčeková et al., 2023) Circularity indexes (using http://circulareconomytoolkit.org); using CN_Con tool; using Circular Spidermap; using Circular Design Tool) (Ruiz-Pastor et al., 2024) System circularity indicator (Gomes et al., 2022; Shin and Kim, 2024)

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Figure A1 Tables 5-8 from (Shin and Kim, 2024)

Table 5
Score for each layer (LK) [24,29].

Layer	Site	Structure	Skin	Services	Space plan	Stuff
Score	0.1	0.2	0.7	0.8	0.9	1.0

Table 7
Connection accessibility [68].

Connection accessibility	Score
Freely accessible without additional actions	1.0
Accessible with additional actions that do not cause damage	0.8
Accessible with additional actions with fully repairable damage	0.6
Accessible with additional actions with partially repairable damage	0.4
Not accessible—irreparable damage to the product or surrounding products	0.1

Table 8
Independency [68].

Independency	Score
No independency—modular zoning of products or elements from different layers.	1.0
Occasional independency of products or elements from different layers.	0.4
Full integration of products or elements from different layers.	0.1

Table 9
Geometry of product edge [68].

Geometry of product edge	Score
Open, no obstacle to the (interim) removal of products or elements.	1.0
Overlapping, partial obstruction to the (interim) removal of products or elements.	0.4
Closed, complete obstruction to the (interim) removal of products or elements.	0.1

Table 6
Types of connections [24].

Connection type		Score
Dry connection	Dry connection (Loose (no fastening material))	1.0
	Click connection (Connection using click system)	
	Velcro connection (Connection using Velcro)	
	Magnetic connection (Connection using Magnetic)	
Connection with added elements	Spring connection (Connection using spring type)	0.8
	Corner connections (Using corner connections)	
	Screw connection (Connection using screw)	
	Bolt and nut connection (Connection using bolt and nut)	
Direct integral connection	Pin connection (Connection using pin)	0.6
	Nail connection (Connection using nail)	
Soft chemical compound	Caulking connection (Connection using caulking)	0.2
	Foam connection (Connection using foam)	
Hard chemical connection	Glue connection (Connection using glue)	0.1
	Pitch connection (Connection using pitch)	
	Weld connection (Connection using weld)	
	Cement bond (Connection using cement bond)	
	Chemical anchors (Connection using chemical anchors)	
	Hard chemical connection (Connection using hard chemical material)	

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