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Research paper

BCEF: Early design framework for circular and low-impact buildings

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ABSTRACT

The transition to a circular economy in construction demands robust frameworks to assess circularity across the building life cycle. Most existing methods lack methodological depth, fail to support early design, and overlook strategies for disassembly, reuse, and service. This paper presents the Building Circularity Evaluation Framework (BCEF), a multi-criteria framework integrating six indicators: Global Warming Potential, Land-Use Footprint, Reused Content, Disassembly Potential, Functional Adaptation, and Product-Service Systems. Aligned with EN 15804+A2, EN 15978, and ISO 20887, BCEF uses digital tools (Brightway2, DeCon) for semi-automated scoring. Validation is conducted using the Circl Pavilion in the Netherlands; one of the few fully disassemblable buildings. Three scenarios with varying circular strategies are modeled to demonstrate BCEF's ability to quantify trade-offs, support early-stage decision-making, and benchmark circularity. Results confirm their robustness, replicability, and relevance for designers, engineers, and policymakers aiming to implement circular construction practices.

1. Introduction

1.1. Background

The building sector is among the most resource- and carbon-intensive industries worldwide, accounting for 36.4 % of material waste in the European Union (EU) [1,2] and nearly 50 % globally [3]. It is also responsible for approximately 40 % of global CO_2 emissions [4], arising from energy-intensive material production, construction activities, building operation, and end-of-life (EoL) processes. A fundamental structural driver of these impacts is the prevailing linear economic model, characterized by a "take–make–dispose" logic that largely neglects strategies for material reuse, recovery, and disassembly during the design phase [5]. As a result, opportunities to reduce embodied emissions and extend material service life remain systematically underexploited.

In response to these challenges, the circular economy (CE) has emerged as a guiding paradigm for reducing resource depletion and environmental burdens. CE aims to maintain products, components, and materials at their highest utility and value over time, supporting restorative and regenerative material cycles [6]. Within the construction sector, this paradigm is reflected in design strategies such as material reuse, design for disassembly (DfD) [7], functional adaptability, and service-based procurement models, which collectively aim to minimize virgin resource input and enhance recovery at EoL [8,9]. At the regulatory and standardization level, CEN/TC 350 [10] provides a European framework defining principles, boundaries, and assessment methods to support the integration of circular economy concepts into construction practice.

Circular construction, therefore, seeks to deliver buildings that

Abbreviations: BCEF, Building Circularity Evaluation Framework; BCIs, Building circularity indicators; CBA, Circular building assessment; CDW, Construction and demolition waste; CE, Circular economy; CLT, Cross-laminated timber; DfD, Design for disassembly; DfD&A, Design for disassembly and adaptability; DfF, Design for flexibility; EC, European Commission; EoL, End of life; EPD, Environmental product declaration; EU, European Union; FCRBE, Facilitating the circulation of reclaimed building elements in Northwestern Europe; GHG, Greenhouse gas; GWP, Global warming potential; HVAC, Heating, ventilation, and air conditioning; ISO, International Organization for Standardization; KPIs, Key performance indicators; LCIA, Life cycle impact assessment; LU, Land-Use footprint; PSS, Product-service systems; RC, Reused content; RES, Renewable energy systems; TQM, Total quantity of materials.

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incorporate reused or recycled materials [11], adapt to changing functional requirements over time, and act as material reservoirs at the end of their service life [12]. By reducing dependence on virgin resources, such approaches are expected to mitigate material scarcity risks and exposure to price volatility [13,14]. In this context, the effective management of Construction and Demolition Waste (CDW) has been identified as a critical enabler of circular transition, highlighting the importance of integrated, life-cycle-oriented resource recovery strategies [15].

To operationalize these principles, a growing number of frameworks and tools have been developed over the past decade, including Level(s), BREEAM, Madaster, and the Whole Building Circularity Indicator (WBCI). These approaches have contributed valuable qualitative and quantitative indicators for assessing aspects of building circularity, particularly material efficiency and disassembly potential. However, they remain heterogeneous in scope and methodology, with limited consistency in life-cycle coverage, indicator integration, and early-stage applicability [16,17]. In particular, environmental life-cycle impacts are not always systematically integrated with circularity metrics, and methodological assumptions are often implicit or tool-specific. These limitations motivate further research into structured approaches that can link circular design strategies with life-cycle impact assessment in a transparent and design-relevant manner.

1.2. Research gap

Despite increasing policy attention and a rapidly expanding body of academic work, standardized and analytically consistent methods for evaluating building circularity across the full life cycle remain limited. Existing approaches are characterized by methodological heterogeneity, including divergent definitions of circularity, inconsistent indicator sets, and varying system boundaries, which together hinder transparency and comparability across projects [18]. In practice, many frameworks focus on specific aspects of circularity, such as individual material flows or recycled content, while relying on qualitative or checklist-based assessment methods that lack quantitative rigor and reproducibility [19].

Although recent studies have attempted to quantify circular construction strategies, many frameworks still struggle to operationalize circularity assessment at the whole-building scale in a life-cycle-consistent manner [20,21]. In particular, the systematic coverage of life-cycle stages defined in EN 15804 and EN 15978; namely Modules A (product stage), B (use stage), C (end-of-life), and D (benefits beyond the system boundary); is often incomplete or implicit, limiting alignment with standardized environmental assessment practice. This fragmentation complicates the interpretation of circularity outcomes and their integration with life-cycle impact assessment results.

Furthermore, empirical evidence suggests that increased circularity does not automatically translate into improved environmental or economic performance [22,23]. Reuse and recycling strategies may shift impacts across life-cycle stages or introduce new trade-offs, underscoring the need for evaluation frameworks that can explicitly relate circular design strategies to quantified life-cycle outcomes. While existing tools such as the Material Circularity Indicator (MCI) and Level(s) provide valuable insights [24], they typically do not integrate disassembly potential, functional adaptability, and service-based models within a unified, quantitative framework at the whole-building level [25]. Moreover, they rarely make explicit how circularity indicators interact with environmental impacts across Modules A–D [26,27].

Taken together, the research gap addressed in this study is not the absence of circularity metrics per se, but the lack of a structured, transparent, and early-stage-oriented evaluation framework that explicitly links circular design strategies with life-cycle assessment principles while acknowledging potential trade-offs.

1.3. Objectives and contributions

This study introduces the Building Circularity Evaluation Framework (BCEF) as a structured, multi-indicator evaluation framework for assessing building circularity and selected environmental impacts during early design stages. BCEF is not intended as a predictive model or optimization tool, but as a transparent evaluative structure that formalizes how circularity-related indicators can be selected, mapped to life-cycle stages, normalized, and aggregated at the whole-building level. The framework was developed through a systematic review of the literature, alignment with EN and ISO standards, and expert consultation within EU-funded projects and technical committees.

BCEF integrates six indicators; Global Warming Potential (GWP), Land-Use Footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product–Service Systems (PSS); each explicitly linked to life-cycle modules defined in EN 15804 and EN 15978 (Modules A–D). The novelty of BCEF lies in being among the first frameworks to explicitly integrate LCIA indicators (GWP, LU) with circular design indicators (DP, RC, FA, PSS) within a unified early-stage engineering evaluation structure. Existing systems such as DGNB, BREEAM, Level(s), and Madaster either lack early-stage engineering applicability, integrated weighting logic, or explicit disassembly assessment; BCEF addresses all three within a single, standards-aligned framework.

To support operationalization, BCEF combines digital tools, including the Brightway life-cycle assessment software for environmental modeling and a semi-automated expert system (DeCon tool) for assessing disassembly potential. This integration enhances transparency and replicability of calculations, while acknowledging the constraints of early design information.

The research addresses the following questions:

1. How can building circularity be evaluated in a structured and transparent manner during early design stages using a life-cycle-based perspective?
2. How can circularity-related indicators be consistently mapped and aggregated across life-cycle Modules A, B, C, and D to support comparative design assessment?

The novelty of BCEF relative to existing international frameworks is threefold. First, it is the first framework to explicitly map six circularity-related indicators–including qualitative dimensions such as Functional Adaptation (FA) and Product–Service Systems (PSS); to life-cycle modules A–D as defined in EN 15804 and EN 15978, enabling joint interpretation of circular design strategies and quantified environmental impacts. Second, BCEF integrates a semi-automated expert system (DeCon) for disassembly potential assessment, making scoring transparent and reproducible rather than judgment-based. Third, it is validated through a real stress-test case (ABN AMRO Circl Pavilion) across three scenario scopes, exposing scope-dependent trade-offs that prior frameworks such as BCI, WBCI, and Level(s) do not model [27,28,30]. Unlike these frameworks, BCEF couples circularity proxies (DP, RC, FA, PSS) with LCIA-based pressures (GWP, LU) within a single normalized composite index, enabling trade-off visualization at the early design stage rather than isolated optimization of either dimension.

The framework is demonstrated through application to the ABN AMRO Circl Pavilion in the Netherlands [26], an information-rich case selected to test internal coherence, indicator behavior, and methodological consistency under real design conditions. The case study is not intended to represent typical building practice, nor to establish generalizable benchmarks, but to illustrate how BCEF can be applied in practice and to identify strengths and limitations of the framework.

Overall, this work contributes a standards-aligned and transparent methodological structure for early-stage circularity evaluation. By explicitly acknowledging trade-offs, methodological assumptions, and current limitations, BCEF provides a foundation for future refinement, comparative testing against alternative frameworks (e.g., Level(s) [28], BCI [29], Madaster [30]), and broader validation across building types and contexts [27,31].

This work aligns with the aims and scope of this journal by addressing a concrete engineering problem: the absence of a structured, quantitative framework for evaluating building circularity during early design–and by developing and validating an engineering solution grounded in life-cycle assessment (EN 15804+A2, EN 15978) and structural performance principles (ISO 20887). BCEF is operationalized through digital engineering tools (Brightway2, DeCon) and validated on a real, constructed, and subsequently deconstructed building. The contribution is methodological and engineering-focused: it produces reproducible, quantitative outputs; GWP in kg CO_2eq, disassembly potential in percentage, and a composite BCEF index; that directly support design engineers and building performance practitioners. This positions BCEF firmly within the domain of structural and environmental engineering, addressing performance engineering challenges rather than management, economics, or social science questions.

2. Relation to recent literature (2020–2025)

A rapidly expanding body of work published between 2020 and 2025 has advanced circularity assessment in the built environment, with BCEF directly building upon and differentiating itself from this recent literature. Khadim et al. [16,27] proposed the Whole Building Circularity Index (WBCI), which advances building-level scoring but does not integrate life-cycle impact assessment (LCIA) indicators or explicit module mapping across Modules A–D. Van Stijn et al. [17] introduced a CE-LCA approach linking material flows to environmental impacts, yet without a disassembly potential indicator or product–service system dimension. Studies by Durmisevic [16] and Slobbe et al. [22] further reinforced the need for early-stage, quantitative evaluation frameworks integrating both circularity and environmental performance dimensions. At the standardization level, the ongoing development of prEN 17998 (design for circularity) and prEN 18177 (framework and definitions) within CEN/TC 350/SC 1 signals institutional convergence toward harmonized European approaches; BCEF is explicitly structured to align with these emerging standards [52,53]. In contrast to the contributions above, BCEF provides an integrated, normalized, and digitally operable structure that simultaneously addresses material circularity, environmental impact (GWP, LU), functional adaptability, and service models within a single composite index–a combination not achieved by any single prior framework. Critically, the Circl Pavilion validation was conducted following the building's actual deconstruction in 2024, providing empirical grounding against real disassembly outcomes that earlier studies could not access [78,79]. This positions BCEF as a methodological contribution directly responsive to the unresolved gaps identified in the most recent literature.

This study makes a direct contribution to building engineering practice by providing a structured, quantitative decision-support framework applicable at the early design stage. The BCEF framework integrates engineering design principles, lifecycle performance assessment, and material circularity metrics into a coherent evaluation methodology. As such, it advances the field of sustainable building engineering by translating high-level environmental goals into actionable, performance-oriented design criteria that can be operationalized by engineers and architects during the pre-design and schematic phases. The framework has been validated through application to a real, constructed, and subsequently deconstructed building, demonstrating its practical utility and reproducibility in engineering contexts.

3. Literature review

The literature on circular economy (CE) assessment in the building sector has expanded rapidly over the past decade, driven by European policy initiatives, standardization efforts, and growing concern over the environmental impacts of construction. Numerous frameworks, indicators, and tools have been proposed to operationalize circularity concepts at material, component, and building scales. However, this body of work is characterized less by convergence than by diversification, resulting in a fragmented assessment landscape with significant variation in scope, methodological rigor, and intended use.

Rather than reviewing these approaches descriptively, this section critically examines how existing frameworks conceptualize circularity, which life-cycle stages and design decisions they address, and where methodological limitations persist. The objective is not to establish a comprehensive taxonomy of circularity tools, but to identify the specific analytical gaps that motivate the development of the Building Circularity Evaluation Framework (BCEF).

2.1. Typology of circularity frameworks

Existing building circularity frameworks can be grouped into five broad methodological clusters: policy-aligned, design-centric, registry-based, certification-based, and integrated evaluation frameworks [33,34]. These categories reflect differences in assessment purpose, indicator structure, and operational depth rather than differences in ambition or relevance.

Policy-aligned frameworks, such as Level(s) [24] and CESBA [28], are primarily designed to support alignment with European sustainability policies and reporting requirements. They embed circularity within broader environmental performance assessment, often through life-cycle assessment (LCA) indicators such as Global Warming Potential (GWP). However, circularity is addressed indirectly and selectively, with limited operationalization of design strategies such as disassembly, adaptability, or service-based procurement. As a result, these frameworks provide policy consistency but limited design-stage guidance.

Design-centric frameworks, including BAMB [29], the Whole Building Circularity Indicator (WBCI) [30], and the Building Circularity Indicator (BCI) [31], place stronger emphasis on architectural and construction-related strategies such as modularity, reversibility, and reuse potential. These approaches are better aligned with early design decision-making but typically rely on qualitative or semi-quantitative scoring methods and partial life-cycle coverage. In many cases, normalization and aggregation procedures are implicit or case-specific, constraining transparency and cross-project comparability.

Registry-based systems, exemplified by Madaster [32], focus on material documentation and traceability through digital building passports. While these tools significantly improve material transparency and reuse potential, they are not performance evaluation frameworks and do not assess environmental impacts, adaptability, or service-life strategies.

Certification-based schemes, such as BREEAM [33], DGBC [34], and DGNB [35], incorporate circularity-related credits within broader sustainability assessment structures. However, circularity criteria are typically dispersed across categories and treated as optional add-ons rather than as a coherent evaluation logic. As a result, circularity performance is difficult to interpret holistically or compare across projects.

Finally, integrated evaluation frameworks aim to combine circularity-related indicators with life-cycle compatibility and early-stage applicability. BCEF is positioned within this emerging category. Its contribution is not the introduction of new indicators, but the explicit structuring, normalization, and aggregation of selected circularity-related and LCIA-based metrics into a transparent evaluation logic suitable for early design comparison. Table 1 summarizes this typology and the main limitations associated with each cluster.

2.2. Comparison of existing frameworks

Several frameworks have attempted to operationalize building circularity in a more quantitative or design-relevant manner [17,36]. Among these, BCI [28] and WBCI [27–48] are frequently cited as early-stage assessment tools. BCI emphasizes material recoverability

Table 1
Typology of building circularity frameworks.

Cluster Type	Defining Characteristics	Example Frameworks	Main Limitations
Policy-Aligned	Broad sustainability goals, use of LCIA, and limited specificity to circularity	LEVEL(s) [24], CESBA [28]	Weak in disassembly (DfD), product-service systems (PSS); not optimized for early design stages
Design-Centric	Conceptual frameworks for architects include some DfD, adaptability, and material recovery.	BAMB [29], WBCI [30], BCI [31]	Often qualitative, limited life cycle (Module D) coverage; lacks standardized KPIs
Registry-Based	Focus on material tracking and digital building passports	Madaster [32]	No performance metrics; limited adaptability and service model integration
Certification-Based	Point-based schemes for compliance; partial inclusion of circularity components	BREEAM [33], DGBC [34], DGNB [35]	Fragmented circularity aspects; lacks integrated, life cycle-based KPIs
Next-Generation Integrated	Normalized KPIs; includes DfD, PSS, and FA; life cycle compatible, digitally operable; first to combine quantitative circularity, modularity, and early-stage decision support	**BCEF** (this article)	Still in early validation phase; limited application across diverse building typologies

and reuse potential, primarily within Dutch policy and planning contexts, while WBCI proposes a building-level score based on modularity, flexibility, and demountability.

Despite their practical relevance, these frameworks exhibit recurring methodological limitations. Life-cycle coverage is often incomplete, with limited treatment of use-phase dynamics (Module B) and benefits beyond the system boundary (Module D). Moreover, indicator normalization, weighting, and aggregation are rarely formalized, which constrains analytical transparency and limits reproducibility. Similar constraints apply to design-oriented frameworks such as BAMB [25–49], which provide valuable conceptual guidance but remain difficult to apply quantitatively during early design stages.

Policy-oriented and certification-based frameworks, including Level (s) [23], CESBA [24], DGNB [31], and BREEAM [30], integrate circularity-related elements within broader sustainability assessment schemes. However, circularity indicators are typically dispersed across categories and not systematically linked to life-cycle stages or design decision workflows. Registry-based systems such as Madaster [29] offer detailed material inventories but do not address performance trade-offs between circular strategies and environmental impacts.

Table 2 provides a comparative overview of selected frameworks, highlighting differences in indicator scope, quantitative rigor, life-cycle coverage, and key limitations. Across these approaches, three persistent gaps emerge. First, early-stage applicability remains limited, despite the fact that critical circularity-related decisions are made during conceptual design [38–40]. Second, qualitative but essential aspects of circularity, such as functional adaptability and product–service systems (PSS), are rarely integrated into quantitative assessment structures. Third, inconsistencies in normalization, weighting, and aggregation reduce transparency and hinder meaningful comparison across projects [37].

2.3. Building circularity evaluation evolution frameworks

To situate the proposed framework within the broader development of circularity assessment in the built environment, Fig. 1 presents a timeline illustrating the evolution of key concepts, standards, and evaluation systems between 2000 and 2025. This evolution can be interpreted through four successive stages of increasing methodological maturity, reflecting shifts from conceptual awareness toward structured and partially standardized evaluation practices.

Stage 1: Conceptual Foundations (2000–2014).

Stage 2: Early Evaluation and Compliance-Oriented Systems (2015–2017).

Stage 3: Design-Oriented and Transitional Frameworks (2018–2020).

This phase introduced more design-oriented and digitally supported approaches. Initiatives such as BAMB (Buildings as Material Banks) [25–49] and the Whole Building Circularity Index (WBCI) [27] advanced circular design thinking by integrating concepts of reversibility, adaptability, and material passports into early-stage planning. The publication of ISO 20887:2020 [32] provided standardized guidance on design for disassembly and adaptability. Concurrent updates to EN 15804 [20] and EN 15978 [21] established a clearer foundation for life-cycle-based assessment of construction products and buildings. Despite these advances, implementation across tools and projects remained fragmented, particularly with respect to life-cycle integration and quantitative comparability.

Stage 4: Integrated and Standardization-Oriented Approaches (2021–2025).

Recent developments reflect a growing convergence between circularity assessment, digitalization, and life-cycle methodologies. Platforms such as Madaster, GRO, and certification schemes incorporating dedicated circularity credits (e.g., DGNB) enable more systematic quantification and documentation of circular strategies. Parallel standardization efforts within CEN/TC 350/SC 1, including prEN 18177 (framework and definitions) and prEN 17998 (design for circularity), indicate movement toward harmonized European approaches [52,53]. Although some draft

Table 2
Comparison of selected circularity assessment frameworks.

Framework	Category	Indicators Used	Quant/Qual	Life Cycle Stages	Key Limitation
LEVEL(s) [23]	Policy-aligned	GWP, material use, LCA	Mixed	A–C	Weak in modularity & DfD
CESBA [24]	Policy-aligned	Environmental & social KPIs	Mixed	A–C	Generic, lacks CE specificity
WBCI [27,48]	Design-phase planning	Whole-building LCA metrics	Quantitative	A–C	Lacks design flexibility and PSS
BCI [28]	Design-phase planning	Reuse potential, modularity, circular score	Mixed	C–D	Lacks normalization and early-stage integration
BAMB [25,49]	Design-phase planning	Material reuse, reversibility	Qualitative	Mostly C–D	Hard to apply at the design stage
Madaster [29]	Registry system	Circularity % by material	Quantitative	A–D	Limited to the material registry; lacks performance indicators
DGNB [31]	Certification	DfD, LCA, resource use	Mixed	A–C	PSS not included
BREEAM [30]	Certification	Material reuse, DfD, LCA	Mixed	A–C	Circularity credits vary in scope

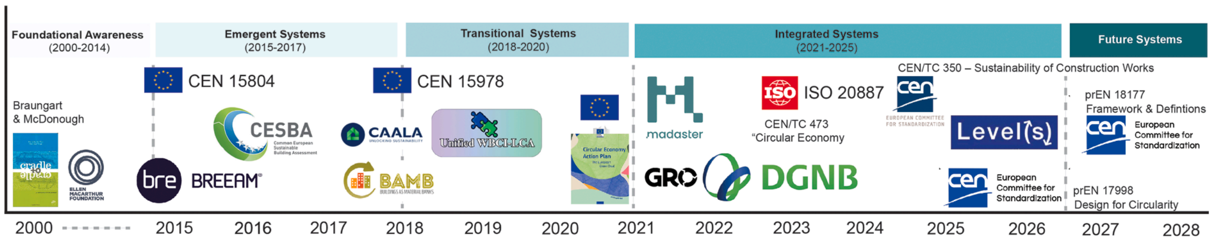

Fig. 1. illustrates the evolution of building circularity evaluation systems from 2000 to 2025 in a timeline.

standards have not yet been formally adopted, they reflect an increasing institutional effort to align circularity assessment with regulatory and life-cycle reporting requirements.

Within this context, the Building Circularity Evaluation Framework (BCEF) is positioned as a design-stage evaluation structure that builds upon, rather than replaces, existing approaches. Its contribution lies in organizing selected circularity-related and life-cycle-based indicators into a transparent, normalized framework intended for early-stage comparison, rather than in establishing a new standard or predictive model.

2.4. Review of circularity indicator development

Across the reviewed frameworks, a recurring set of indicators can be identified, addressing environmental impacts (e.g., GWP, land use), material loops (e.g., reused or recycled content), and design strategies (e.g., disassembly, adaptability). BCEF builds on this established indicator landscape rather than expanding it. Its six indicators; GWP, Land-Use Footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product–Service Systems (PSS); were selected based on their prevalence in the literature, alignment with European and international standards (EN 15804+A2 [24], EN 15978 [25], ISO 20887 [42]), and feasibility of application during early design stages [41–45].

The distinguishing feature of BCEF lies in how these indicators are structured and combined. Rather than treating circularity and environmental performance as parallel or loosely connected dimensions, BCEF explicitly maps circular design strategies to life-cycle stages and integrates selected LCIA indicators to support joint interpretation. This approach reflects emerging trends in frameworks such as Level(s) [22], DGNB [40], and BREEAM [38], while making underlying assumptions explicit and transparent.

2.4. Rationale for the BCEF framework

The literature review demonstrates that existing frameworks provide valuable but partial perspectives on building circularity. Most either prioritize policy alignment, conceptual design guidance, or material documentation, but lack a transparent evaluation structure that connects circular strategies with life-cycle impacts at the whole-building level during early design.

BCEF responds to this gap by offering a structured evaluation framework that formalizes indicator selection, life-cycle mapping, normalization, and aggregation to support quantitative comparison of design alternatives at the whole-building level. By integrating existing indicators within a coherent, standards-aligned structure, BCEF aims to support informed comparison of design alternatives and to complement, rather than replace, existing frameworks and guidelines [55–57].

The following section details the methodological development of BCEF, grounded in the critical insights derived from this review.

4. Methodology

BCEF is conceived as a structured evaluative framework for organizing, comparing, and interpreting circularity-related indicators during early design stages, when information is incomplete, and design flexibility is still high. The framework formalizes how indicators are selected, mapped to life-cycle stages, normalized, and aggregated, while explicitly acknowledging the role of expert judgment and data constraints.

3.1. Analytical approach

The development of the Building Circularity Evaluation Framework (BCEF) followed a multi-phase analytical approach grounded in literature review, regulatory alignment, and expert consultation.

In the first phase, a descriptive and comparative analysis was conducted of existing circularity frameworks and indicators. This involved extracting data from published reports, peer-reviewed case studies, and technical documents to identify key characteristics of building circularity indicators (BCIs). Each framework was examined with respect to its:

(a) underlying assumptions and limitations,
(b) theoretical foundations (e.g., circular economy definitions, scope, KPIs, and R-strategies),
(c) maturity level (emerging, in development, or fully implemented), and
(d) calculation approach (qualitative or quantitative).

To complement this analysis, a structured literature review was performed. The literature review was conducted using Scopus (for peer-reviewed journal and conference publications) and Google Scholar (to capture grey literature and emerging sources). Web of Science was not included, as preliminary testing revealed high overlap with Scopus but lower coverage of technical reports and EU project deliverables relevant to circularity in the built environment.

More than 200 peer-reviewed publications from 2010 to 2023 in English, Dutch, Danish, and German were screened using keywords such as "circularity indicators," "disassembly criteria," and "barriers to circular construction", in a previous research by the authors of this paper [16]. The timeframe 2010–2023 was selected because circular economy concepts began to be systematically applied to the building sector after 2010, following the establishment of the Ellen MacArthur Foundation and subsequent EU policy initiatives (see Fig. 1). Earlier publications (pre-2010) were primarily focused on waste minimization and recycling, without addressing building-level circularity frameworks. After title and abstract screening, 87 articles were selected for full-text analysis based on methodological relevance and contribution to indicator development. Special attention was given to disassembly-related criteria and implementation barriers, which informed both the selection and operationalization of indicators within BCEF. These barriers align with findings from international expert surveys, which highlight institutional, financial, and technical challenges to adopting the circular economy within the construction industry [13].

The final indicator set was refined through expert consultations organized within two European initiatives: the FCRBE project (2019–2023) and COST Action CA21103 (2022–2025). In total, 15 professionals from Belgium, the Netherlands, France, and Germany participated, representing academia, architectural practice, engineering, and policymaking. These consultations were conducted as structured focus group workshops intended to assess practical relevance, clarity, and early-design applicability rather than to perform formal indicator validation. The process followed four steps: (1) presentation of candidate indicators identified from the literature, (2) moderated discussion on measurability and policy alignment, (3) qualitative scoring against predefined criteria, and (4) iterative discussion leading to consensus. This process does not constitute a Delphi study or a statistical validation exercise; instead, it serves to ensure that the indicator set reflects practitioner-informed operational relevance. Summaries of these consultations are provided in Appendix 1.

The selection of six KPIs, Global Warming Potential (GWP), Reused Content (RC), Land-Use Footprint (LU), Disassembly Potential (DP), Functional Adaptability (FA), and Product-Service Systems (PSS), was based on a triangulated method combining (i) frequency in academic literature, (ii) alignment with European regulatory frameworks

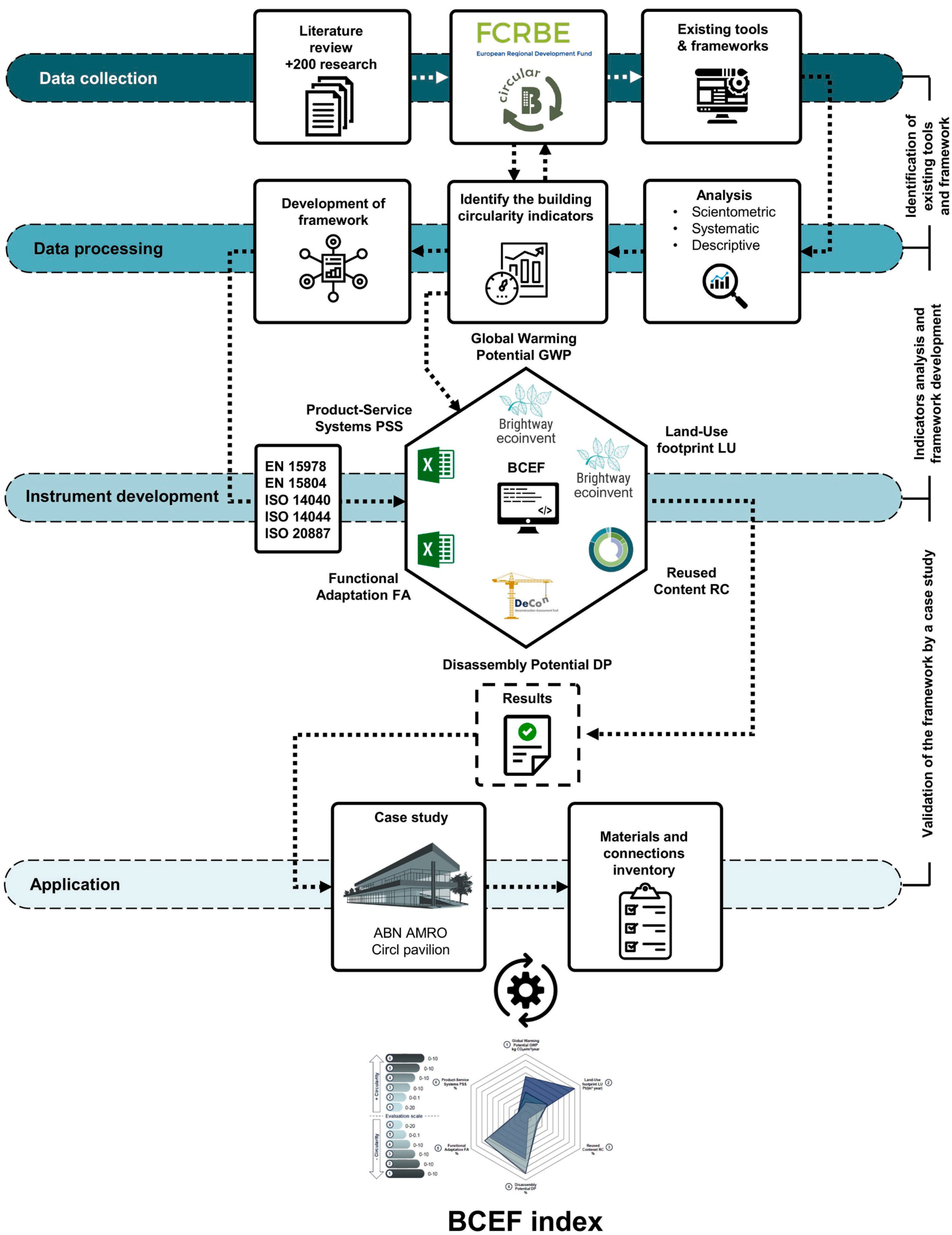

Fig. 2. Methodology framework of the research.

including LEVEL(s), ISO 20887, EN 15978, and the EU Circular Economy Action Plan [46–74], and (iii) expert consensus building through the initiatives above. These sessions enabled the refinement, ranking, and validation of candidate indicators based on their clarity, feasibility, transferability, and utility for decision-making. The inclusion of GWP and LU, while not direct measures of circularity, was justified to capture the environmental consequences of circular strategies and avoid burden shifting. The final indicator set represents a consensus-based operationalization informed by stakeholder input and builds on the authors' prior work in the field [16,59]. The resulting KPI set should therefore be interpreted as a consensus-based operational selection, not as an exhaustive or statistically optimized representation of building circularity.

Each indicator was critically assessed to determine appropriate data sources, calculation techniques, and integration within the life-cycle-based framework. Indicator weights were derived through structured expert elicitation involving six experts from academia and industry, including representatives from Colruyt Group. The process consisted of two focus group rounds aimed at achieving convergence rather than statistical consistency. Experts discussed indicator relevance based on measurability, regulatory alignment, and design-stage usefulness. No formal analytic hierarchy process (AHP), best–worst method (BWM), or consistency testing was applied. Weighting outcomes should therefore be interpreted as context-sensitive prioritizations reflecting current European circular building practice, rather than as universally optimal values.

To validate the framework, the ABN AMRO Circl Pavilion in Amsterdam was selected as a case study. The building exemplifies circular economy principles through its design for disassembly (DfD), use of reused materials, and service-based product models. The application of BCEF to this real-world case demonstrated the framework's feasibility and relevance. In addition, preliminary usability testing with professionals helped inform the framework's presentation and functionality, though no formal user experience study was conducted [75]. Finally, the indicator results were synthesized into a visual radar chart (Fig. 2), providing a holistic view of the building's circularity performance. This graphical representation supports early-stage design decision-making by clearly illustrating strengths and trade-offs across the six KPIs.

3.2. Development of the framework

Building on the analytical approach and indicator definitions established in Sections 3.1 and 3.2, this section outlines how the Building Circularity Evaluation Framework (BCEF) synthesizes diverse circularity metrics into a structured and actionable assessment framework. The framework was created with the explicit goal of supporting early design decision-making in circular building projects. This structured scoring approach was subsequently applied to a real-world case study to validate the framework's performance.

The six indicators, Global Warming Potential (GWP), Land-Use Footprint (LU), Reused Content (RC), Disassembly Potential (DP), Functional Adaptation (FA), and Product-Service Systems (PSS), were operationalized based on international standards (e.g., EN 15804+A2, EN 15978, ISO 20887), validated with experts, and tested on a real-world office building case. Each indicator captures a distinct dimension of building circularity across the full life cycle and is linked to specific life cycle stages as defined by EN 15804+A2:

- GWP and LU: assess Modules A, B, and C (product, use, and end-of-life stages [76])
- DP: focuses on Module C (deconstruction and waste processing)
- RC, FA, and PSS: emphasize Module D (potential benefits and reuse)

Each indicator is normalized to a 0–1 scale using min-max normalization, ensuring comparability across different units and value ranges. The direction of normalization depends on whether a higher raw value corresponds to better or worse circular performance. Min–max normalization was selected due to its transparency, low data requirements, and compatibility with early-stage design information, rather than to imply statistical optimality or uncertainty minimization.

3.2.1. Indicator normalization formulas

Negative Indicators (e.g., GWP, LU):

$$S_i = 1 - \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{1}$$

Positive Indicators (e.g., RC, DP, FA, PSS):

$$S_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{2}$$

where:

X_i = actual value of the indicator.

X_{min} and X_{max} = empirical bounds for normalization.

3.2.2. Composite circularity index

To produce a single composite score for circularity, a weighted sum of the normalized indicator scores is computed. The composite BCEF index is intended as an interpretive aggregation to support comparison between design options, not as a predictive or decision-optimizing metric:

$$BCEF_{index} = \left(\sum_{i=1}^{n} W_i \, . \, S_i\right) X\ 100 \tag{3}$$

W_i = weight of the i indicator.

S_i = Normalized score of the i indicator.

n = Total number of indicators.

The weights used in this article were determined through a combination of expert consultation and literature review:

- GWP = 0.25
- LU = 0.15
- RC = 0.20
- DP = 0.15
- FA = 0.15
- PSS = 0.10

These weights ensure that the relative contribution of each indicator to the final score reflects its practical and environmental importance. The final weights reflect the consensus outcomes of this expert-based consensus building, with sustainability experts from academia and industry aligning with circularity priorities defined in European building sustainability research. Indicator weights were assigned through a two-step process. First, a literature review was conducted to identify weighting approaches in existing frameworks, including BCI [Kibert, 2016], WBCI [Khadim et al., 2023], DGNB Circularity Indicators (2021), and CE-LCA [17]. Second, expert workshops were held with 15 participants from academia, practice, and policymaking. Experts scored each candidate indicator against three predefined criteria: measurability, policy relevance, and design applicability. Scores (1–5) were aggregated, and results were refined through iterative group discussion and consensus voting. This ensured that final weights reflected both scientific grounding and practical utility.

To test the robustness of the Building Circularity Evaluation Framework (BCEF) and explore the influence of design scope on circularity outcomes, three distinct calculation options were defined for the case study [77]. These options represent different levels of circular integration and disassembly potential, based on the components included in the assessment:

- **Calculation Option 1**: Full-building baseline scenario. This option includes all building elements, including the basement and foundation components. It represents the actual constructed state of the building and serves as the baseline for comparison.
- **Calculation Option 2**: Above-ground scenario. This option excludes the basement and focuses only on components that are more readily recoverable or dismantlable, such as the timber superstructure and enveloping systems.
- **Calculation Option 3**: Optimized circularity scenario. This option includes only those elements that were explicitly designed for disassembly, reuse, or integration through product-service systems. It reflects a best-practice approach based on intentional circular design choices.

These scenarios facilitate a comparative evaluation of circularity indicators under varying design and construction assumptions, offering insights into how design intent and scope impact overall circularity performance.

3.3. Visual representation and application

The results are synthesized using a radar chart, offering a clear graphical summary of the building's performance across all six indicators. This visual format aids communication with design teams, clients, and policymakers by highlighting strengths and areas for improvement. Finally, the framework's flexibility and transparency allow for future adaptation. Additional indicators can be integrated, and weighting schemes can be modified to fit different project contexts or stakeholder priorities. A sensitivity analysis was conducted to assess the robustness of the BCEF Index under various assumptions.

3.4. Sensitivity analysis

A sensitivity analysis was conducted to test the robustness of the BCEF results against parameter variation. We applied a one-at-a-time (OAT) approach, varying indicator weights by ± 20 % and normalization bounds (Xmax, Xmin) by ± 10 %. The BCEF scores were recalculated under these variations. Results indicated that while absolute scores shifted, the relative ranking of design scenarios was unaffected, confirming the stability of the framework.

4. Validation

4.1. Case research

The ABN AMRO Circle Pavilion [78] is a 3350 m^2 project developed by the investment bank ABN AMRO [79] adjacent to its headquarters in Amsterdam. It is one of the earliest examples of buildings designed in accordance with circular economy principles. The pavilion is located at Gustav Mahlerplein in Zuidas, near Zuid station, and in front of the main building of ABN AMRO. The building was designed by de Architekten Cie [80] and constructed by the Royal BAM Group [81], with completion scheduled for 2017. The project prioritized the use of recycled materials and significantly reduced the embodied carbon (GHG emissions) of its construction. Notably, Circl deviated from traditional bank architecture by omitting materials commonly found in similar buildings, such as marble floors and elaborate glass and steel components. This approach resulted in a reduction in material use by approximately one-third, or 2425 tons, compared to the original plans.

All materials, components, and parts that make up the building have been recorded in a 'digital twin'; the building passport is named LLMNT. Moreover, renewable energy comes from solar panels on the building's roof to reduce GHG emissions during the use stage (Module B6). However, the emphasis on recycled materials posed a unique challenge. Obtaining a building permit was delayed because the project relied on the availability of materials, which influenced the final design. This approach, in which materials dictate design rather than conform to a predetermined architectural plan, is uncommon in contemporary commercial real estate but reflects traditional building practices seen in historical structures (see Fig. 3).

4.2. Inventory and inspection campaign

4.2.1. Building materials

To quantify the building materials, a hybrid approach was employed. Primary data were derived from the architectural plans, technical documentation, and detailed material specifications provided by the design team (de Architekten Cie) [80]. Where complete quantity data were unavailable, additional estimates were generated using reliable open-source databases and platforms, including the de Architekten Cie project repository, Bouwkosten.nl, NIBE Milieu Classificaties, and manufacturer product datasheets. Quantities were calculated through scaled take-offs from architectural drawings and cross-checked using material density benchmarks to enhance accuracy.

Additionally, the project utilized the LLMNT digital twin and material passport, which documents all components and materials present in the building. The LLMNT database was consulted to validate and supplement the inventory data, particularly in identifying reused, recycled, and service-based components. By combining drawing-based estimation with digital asset information, the final material inventory achieved both precision and transparency. This integrated methodology ensures a robust and reproducible foundation for subsequent circularity assessment.

Table 3 provides a breakdown of the primary material groups by weight. The structure used Dutch timber from DERIX [82] as a substitute for concrete, and incorporated locally sourced materials. Approximately 850 m^3 of pine CLT was used for the building structure. Simultaneously, some partition walls were repurposed from the façade of a previous building. The hardwood flooring on the ground floor was salvaged from a former monastery and a Dutch football club, and the insulation was created by recycling 16,000 pairs of jeans. Fig. 4 illustrates the weight share of each material in the building.

PV panels were excluded from the circularity index calculation due to their negligible disassembly potential and the reuse of content in the current design. They remain accounted for in environmental modeling (GWP) but were removed from material-mass-based circularity indicators to avoid inflating the index with functionally irrelevant mass. Their inclusion allows for the evaluation of embodied carbon and potential reuse. Furthermore, PV panels can be subject to product-service system contracts, in which ownership and responsibility remain with the manufacturer. Although they do not significantly contribute to the reuse of content or disassembly potential indicators unless specifically reused or leased, their relevance lies in their potential to reduce operational emissions and support long-term circular strategies, especially in the context of modular renewable energy systems.

As shown in Fig. 5, other circular inputs [83] were observed during the inventory and inspection process in this project: the plastered walls and felt on the stands contained old work clothing, second-hand fire hose reel cabinets were used, and the wall finishing was made of residual wood. The ventilation ducts are constructed using sustainable textiles. Interior and exterior claddings heavily utilize FSC-certified wood and reused wood from other construction sites. More than 2500 kg of old ABN AMRO corporate clothing was recycled to create acoustic walls. The lifts in Circl have not been purchased but have been leased and will return to the manufacturer after 10 years. Moreover, renewable energy can be generated from solar panels on the roofs of buildings, thereby reducing GHG emissions during use.

4.2.2. DfD and building connections

The building is designed for disassembly and reuse [79]. Building design facilitates future reuse and recycling, ensuring that many of these components can be repurposed at the end of a building's lifespan. This

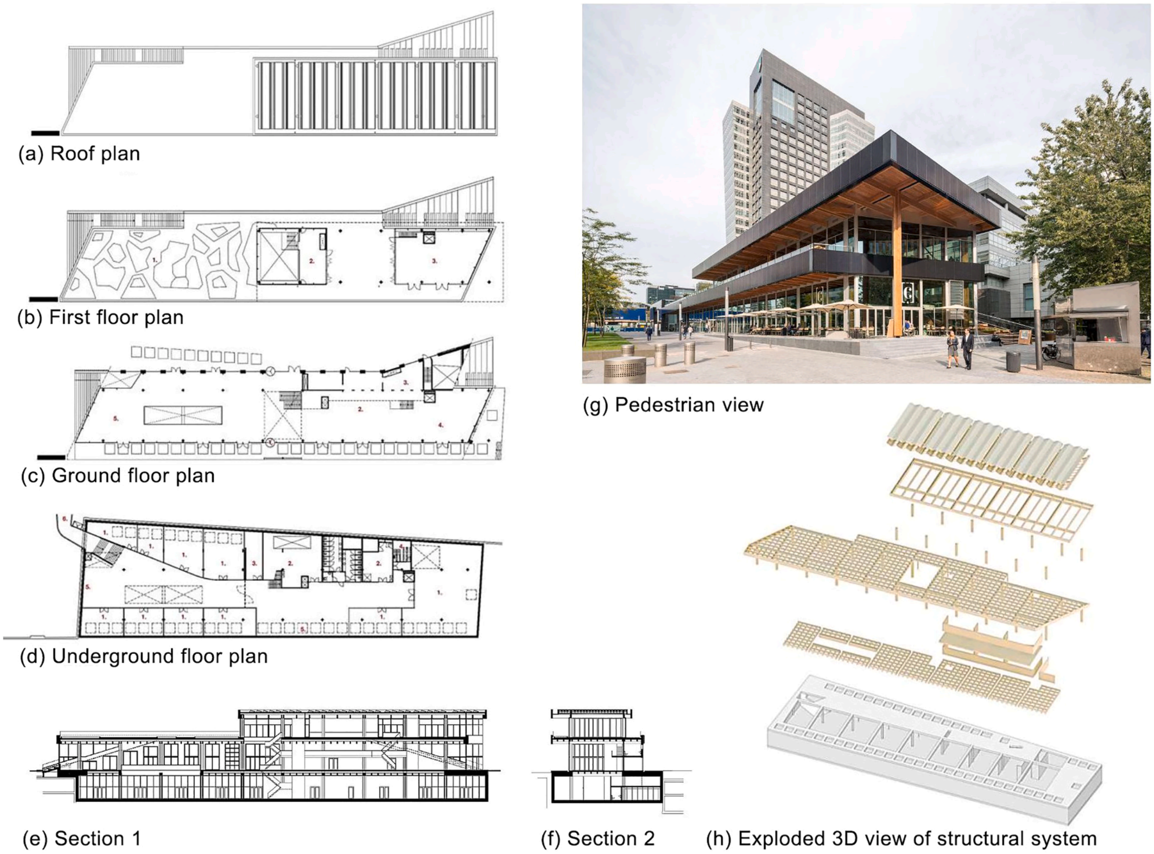

Fig. 3. Case study building visualizations. (a) Roof plan; (b) First floor plan; (c) Ground floor plan; (d) Underground floor plan; (e) Section 1; (f) Section 2; (g) Pedestrian view; (h) Exploded 3D view of structural system [80].

Table 3
Breakdown of primary material groups based on their weight.

Building material groups	ABN AMRO Circl pavilion	
	Amount [kg]	Share [%]
Concrete	5245,440	81.41
Timber	912,458	14.16
Steel	173,741	2.70
Glass (windows & doors)	72,000	1.12
Galvanized steel	7679	0.12
Solar panels	7540	0.12
Roof insulation	7400	0.11
Glass (partitions)	5500	0.09
Aluminum	3900	0.06
Air handling unit	3900	0.06
Services and cables (copper, plastic, etc.)	3800	0.06

was achieved through the use of modular construction techniques. Bolted rather than welded connections were used to facilitate disassembly. The wooden structure is detailed in such a way that hardly any holes need to be drilled, which means that the beams will be easy to reuse should the construction need to be disassembled. The façade consists of demountable glass panels that can be separated and reused. The floors are composed of modular raised units that can be easily removed and repurposed.

To evaluate the disassembly potential of a building, it is essential to inventory its products, components, and connection types, as well as any disassembly barriers that may be present. This article categorizes the building elements into seven primary groups: structure, foundation and basement, envelope, roof, interior, finishing, and technical systems. In the Circl case study, a detailed analysis was conducted to identify the key products, component assemblies, and connection methods used within each category. The structural components include columns, beams, joists, and slabs. Two components were identified for the foundations: concrete rafts and concrete walls. The following components were considered for the roof: beams, insulation, wood-fiber panels, and solar panels. Roof gravel was excluded from this research. Furthermore, four main types of façades were identified: glazed sections, recycled aluminum curtain wall frames, green walls, and photovoltaic panel cladding. All the interior and finishing components were also considered.

The connection types and their scores were considered, assuming that the same type of connection was used for each connection. Therefore, the result is the same using the expert system (DeCon tool) unless there are defects or barriers in specific connections, as observed in the foundation connections and some structural connections by the authors during the building dismantling process, as will be mentioned in the discussion section. The DP of the building, according to the second beta version of the expert system (DeCon tool) [2], is addressed in the Results section. Table 4 lists the main connection types in the building, along with their IDs, as classified in a previous article by the authors [2].

4.2.3. Product-service systems (PSS)

Circl, a notable example of sustainable architecture, incorporates innovative circular economy principles through collaboration with PSS companies [84,85]. This approach demonstrates the potential of service-based economic models for advancing circularity.

ABN AMRO Bank owns the *Circl* pavilion, but it does not own everything in the building. For example, Mitsubishi owns a lift. This implies that the lift supplier sells a service (vertical mobility) rather than a product. Mitsubishi provides the lift design and maintenance, and is paid for the proper operation of the lift based on a pay-per-use model. *Circl* receives a discount on annual costs if it uses less than what was

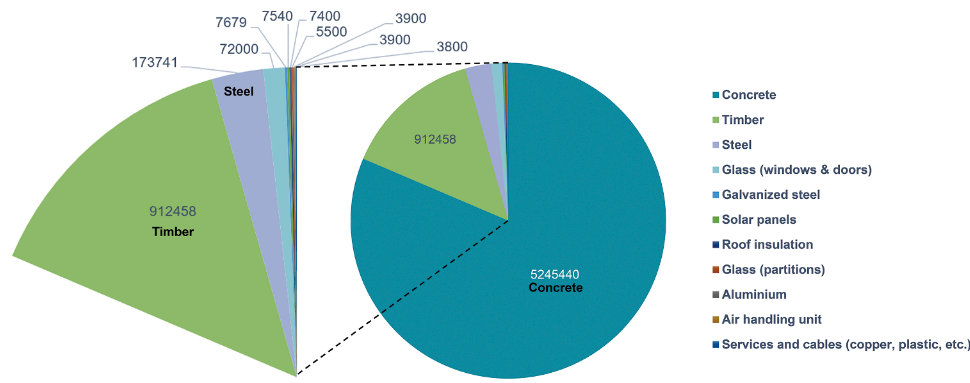

Fig. 4. Material composition of the Circular Pavilion expressed as the percentage share of each material category by total building mass (kg).

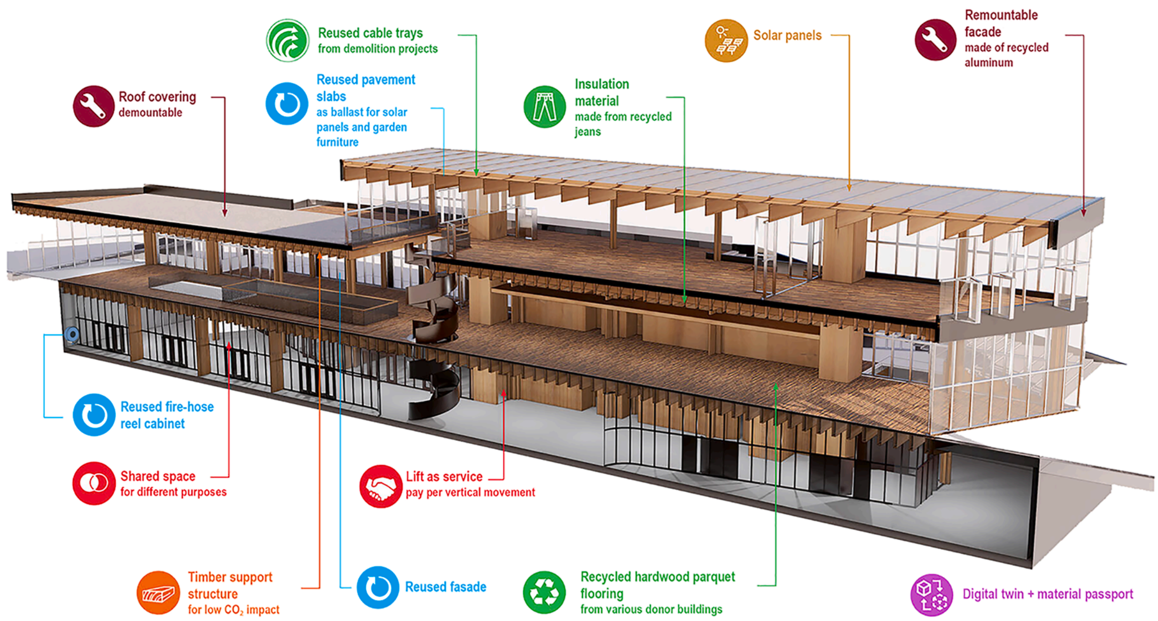

Fig. 5. The circular inputs in the building (*Architect: Hans Hammink, Pi de Bruijn, de Architekten Cie*) [80].

agreed upon in the contract. This model breaks the traditional vertical construction. While the traditional model focuses on short-term building costs, this model emphasizes long-term life cycle costs and value creation. While a long service life reduces the asset turnover ratio, this business model enables companies with high-quality products to compete with traditional, yet lower-quality, products that are cheaper. This is the essence of the change. In addition to the lift, *Circl* Pavilion buys services for audiovisual equipment. There are pay-per-use contracts for more services being tested. The Circl pavilion also has vintage furniture in the form of services. In return, the Circl pavilion serves as a storage area and showroom.

5. Results

To assess the implications of varying levels of circular integration, three calculation options were developed based on the existing Circl pavilion. Although Circl is a real and already constructed building, its disassembly and planned relocation created a unique opportunity to simulate different scenarios for material reuse and system integration. Calculation Option 1 achieved 53 %, reflecting limited disassembly and heavy material use in the basement. While this quantitative outcome is illustrative, the primary purpose of this comparison is to assess the consistency and realism of the BCEF framework's output in relation to the known ground-truth conditions observed during the building's actual deconstruction. This scenario represents the full baseline condition. Calculation Option 2 excludes the basement, focusing only on above-ground, easily recoverable components, thus simulating a realistic partial reuse scenario. Calculation Option 3 further narrows the scope to include only elements that were explicitly designed for disassembly, reuse, or integration through service-based procurement models. This last option represents an optimal case, aligned with best practices in circular construction. The three options allow for a comparative analysis of how circularity indicators respond to variations in building scope and design intent.

A comparative breakdown of the materials and components included in each calculation option is provided in Appendix 2. This additional documentation supports transparency and allows replication of the calculation logic applied in the BCEF framework.

5.1. Global warming potential (GWP)

Based on the life cycle impact assessment (LCIA) results for the Circl pavilion, as shown in Fig. 6, the global warming potential varied significantly for each calculation option. Calculation Option 1 produced a GWP of 12.84 kg CO_2e/m^2/year. In comparison, calculation Option 2 achieved a reduction of approximately 39.6 %, with a footprint of 7.75 kg CO_2e/m^2/year. Calculation Option 3 exhibited the lowest impact, achieving a 63.3 % reduction relative to Calculation Option 1, with a

Table 4
Main building connections, their IDs, and scores according to the expert system (DeCon tool) classification. Scores (0.0 g connections, their IDs, and scores according to the expert system (DeCon tool) classification *s*, as will be mentioned in the discussion section in *t material loss or damage* (e.g., dry or mechanical fixings such as insulation layers, bolted joints), score highest (1.0). Partially reversible connections, such as typical concrete structural joints (e.g., column–beam, slab–wall), receive intermediate scores (≈0.8). Fully cast-in-place or destructive connections (e.g., concrete raft–wall joints) are considered non-reversible and score lowest (0.1).

Category	Connection	Connection ID	Score
Structure	Column & beam	C.e1	0.8
	Column & slab	C.e1	0.8
	Column & bearing wall	C.e5	0.8
	Column & foundation	C.e5	0.8
	Beam & slab	C.e5	0.8
	Beam & conc. slab	C.e3	0.8
	Beam & secondary beams	C.e1	0.8
	Slab & bearing wall	C.e4	0.8
	Bearing wall components	C.e4	0.8
Foundation & Basement	Conc. raft & conc. wall	H.c6	0.1
	Conc. wall & conc. slab	H.c6	0.1
	Conc. column & conc. beam	C.e3	0.8
Envelope	Façade element. & column	C.e4	0.8
	Façade element. & beam	C.e4	0.8
	Façade element. & slab	C.e4	0.8
	Façade element. & floor	C.e4	0.8
Roof	Roof & column	C.e4	0.8
	Roof & beam	C.e4	0.8
	Roof & insulation	D.c1	1.0
Interior	Partition wall & slab	C.e4	0.8
	Partition wall & column	C.e4	0.8
	Glass wall & column	C.e4	0.8
	Glass wall & slab	C.e4	0.8
	Stair & slab	C.e1	0.8
	Railing & slab	C.e1	0.8
Finishing	Floor layers	D.c1	1.0
	Cladding	C.e4	0.8
Technical systems	PV system	C.e5	0.8
	Lighting system element.	C.e4	0.8
	Cables/cable trays	C.e4	0.8
	HVAC system element.	C.e5	0.8
	Firefighting system element.	C.e5	0.8

footprint of only 4.71 kg CO_2e/m^2/year. These different results were attributed to the different quantities of materials used in the three calculation options, which, in turn, affected the resulting GHG emissions.

Although operational energy use (Module B6) appears proportionally small in Fig. 6, this is due to the annualization of results over reference service life. When cumulative values are considered over a typical 50–60-year building lifespan, operational energy remains a dominant contributor to total GWP, often exceeding embodied impacts in most conventional buildings. The BCEF framework reports annualized values to enable comparability across design scenarios, while also acknowledging the long-term significance of operational energy. Future applications of BCEF could incorporate dynamic energy scenarios that account for grid decarbonization pathways and renewable integration, providing a more nuanced picture of B6 contributions over time.

5.2. Land-use footprint

For the land-use footprint, as illustrated in Fig. 7, calculation Option 1 generated a footprint of 0.09 Pt/(m^2·year). In comparison, calculation options 2 and 3 demonstrated a 55 % reduction, achieving a footprint of 0.04 Pt/(m^2·year). This analysis underscores the substantial differences among the calculation options, highlighting the progressive reduction in land-use impacts achieved by lowering material quantities.

5.3. Disassembly potential

Following a comprehensive audit of the building, an inventory detailing the number and types of connections was compiled using an audit sheet (see Appendix 3). These data were then processed using an expert system (DeCon), which the authors developed to evaluate a building's disassembly potential [2]. According to Fig. 8, Calculation Option 1 reveals an overall disassembly potential of 68 % for all connections. However, the disassembly potential in the foundation and basement areas showed a reduction of up to 10 % owing to the use of non-prefabricated underground concrete, which cannot be retrieved without demolition. Furthermore, an additional 10 % decrease was observed after factoring in the disassembly barriers. This highlights the limitations associated with this foundation type, which is a recognized design flaw when aiming for building disassembly. The disassembly assessment of each connection was based on the feasibility of detaching and isolating individual components from the surrounding structures.

Calculation Option 2 achieved an overall disassembly potential of 88 % when the basement was excluded, thus avoiding the related disassembly barriers. The calculations focused on assessing the connections between building products, components, technologies, electrical systems, and other components with high disassembly potential. Buildings must incorporate modular and replaceable components to achieve adaptability, futureproofing, and circularity. For instance, because building services typically have shorter lifespans than structural components, their design should facilitate straightforward disassembly and replacement. This approach can significantly extend the overall service life of buildings.

In contrast, Calculation Option 3 achieved the highest disassembly potential of 90 %, compared to Calculation Options 1 and 2. This calculation option concentrated exclusively on above-ground building products and components, which were specifically designed for disassembly. The disassembly potential reports are provided in Appendices 3, 4, and 5.

5.4. Reused content

As shown in Fig. 9, following a comprehensive inventory of the building materials, the results indicate that Calculation Option 1 had the lowest percentage of reused content at 5 %. This was primarily due to the significant quantities of concrete used in the basement, which significantly contributed to the share of virgin materials in the building. Although the building structure was constructed using sustainably sourced timber, which significantly enhanced the renewable materials indicator after accounting for the neutralization of the basement concrete, the primary construction components were emphasized to be recycled and reused materials. Under Calculation Option 2, the percentage of reused content reached 22 %, which is attributed to the high inclusion of reused components, such as flooring, insulation, and certain components of the HVAC systems. In addition, cables and cable trays from the RES contribute to this percentage. For calculation option 3, the reused content indicator was 20 %. This calculation exclusively considered construction components and materials that were either recycled or reused, including flooring, insulation, aluminum panels used in the façade, and some interior glass partitions.

5.5. Functional adaptation

Functional adaptation was evaluated in accordance with the principles and guidelines outlined in ISO 20887:2020 [86]. Although the building is generally designed with DfA principles, Calculation Option 1 exhibited a lower adaptability score than the other calculation options, reaching only 65 %, as shown in Fig. 10. This was attributed to the use of massive concrete structures during the construction of the basements. The absence of plans to dismantle internal concrete walls renders adaptation or modification neither technically feasible nor economically

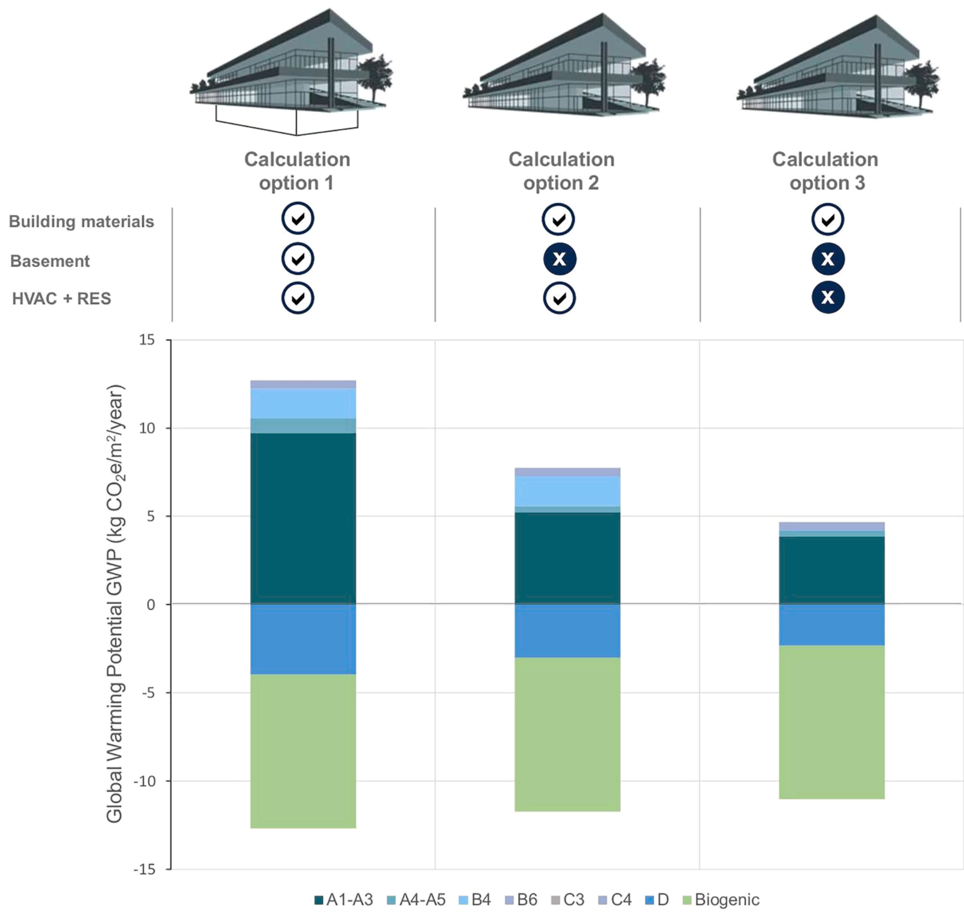

Fig. 6. Contribution of life cycle modules to building GWP (annualized values). Colors have been differentiated for clarity. Negative contributions correspond to Module D substitution credits and biogenic carbon storage, as defined in EN 15804+A2. While operational energy use (B6) appears proportionally small due to annualization, cumulative lifetime impacts remain significant and are discussed in Section 5.

viable. This section of the building serves as an example of a construction practice misaligned with the principles of a circular economy.

In contrast, Calculation Options 2 and 3 achieved identical overall adaptability scores of 75 %, which were higher than Calculation Option 1. This improvement is due to the dismantling nature of all products and components used, which enhances the building's functional adaptation and capacity for expansion. Calculation options 2 and 3 also recorded diversity and transformation scores of 80 % each, owing to the presence of open, flexible spaces that support functional adaptation.

Calculation Option 1 scored 60 % for these same indicators due to the presence of non-removable internal concrete walls at the basement level. Calculation Option 1 demonstrated a vertical expansion potential of 70 %, allowing for the addition of an extra floor or two without requiring substantial modifications to the building's foundation. Calculation Options 2 and 3 recorded the same results if the basement was dispensed. Adopting traditional foundations, such as concrete blocks and rafting, will help increase the possibility of vertical expansion owing to the lightweight nature of the building. Regarding horizontal expansion, none of the three calculation options achieved significant results. It was recorded as 0 %, owing to the absence of any additional areas that could be used or repurposed for future expansion. The building was constructed within the entire plot limit (see Appendix 6).

5.6. Product-service systems (PSS)

After inventorying the services implemented in the building as PSS and evaluating them against the optimal reference case, as detailed in Section 3.2.6, the variance was calculated as 7/50, as listed in Table 5. This placed the building at a score of 14 % on BCEF radar across all evaluated calculation options. This modest result reflects both the nascent state of the PSS metric and inherent challenges in assessing circularity within complex systems. It should be noted that the PSS indicator remains exploratory in nature: the current scoring logic (7/50 reference scale) was developed for this study and requires broader validation across diverse building typologies and procurement contexts before it can be considered a standardized metric. Future refinements may incorporate contractual value retention metrics–such as lease duration, residual value agreements, and manufacturer take-back obligations–to provide a more robust and reproducible basis for PSS assessment within building circularity frameworks.

5.7. Implementation of BCEF

The BCEF index scores from the three scenarios are normalized composite values across six weighted indicators. A score of 65 % or 68 % does not imply that the building is 65–68 % circular in absolute terms, but rather that, relative to the benchmarked best- and worst-case assumptions, the design achieves a moderately high level of circular integration. This includes high disassembly potential, reused content, and minimized environmental impact. These values are intended as comparative decision-support frameworks, not absolute metrics of circularity.

In this case, Calculation Option 1 achieved 57 %, reflecting limited disassembly and heavy material use in the basement. Options 2 and 3, with scores of 67 % and 69 % respectively, approach the threshold of high circularity, primarily due to reduced material intensity and better

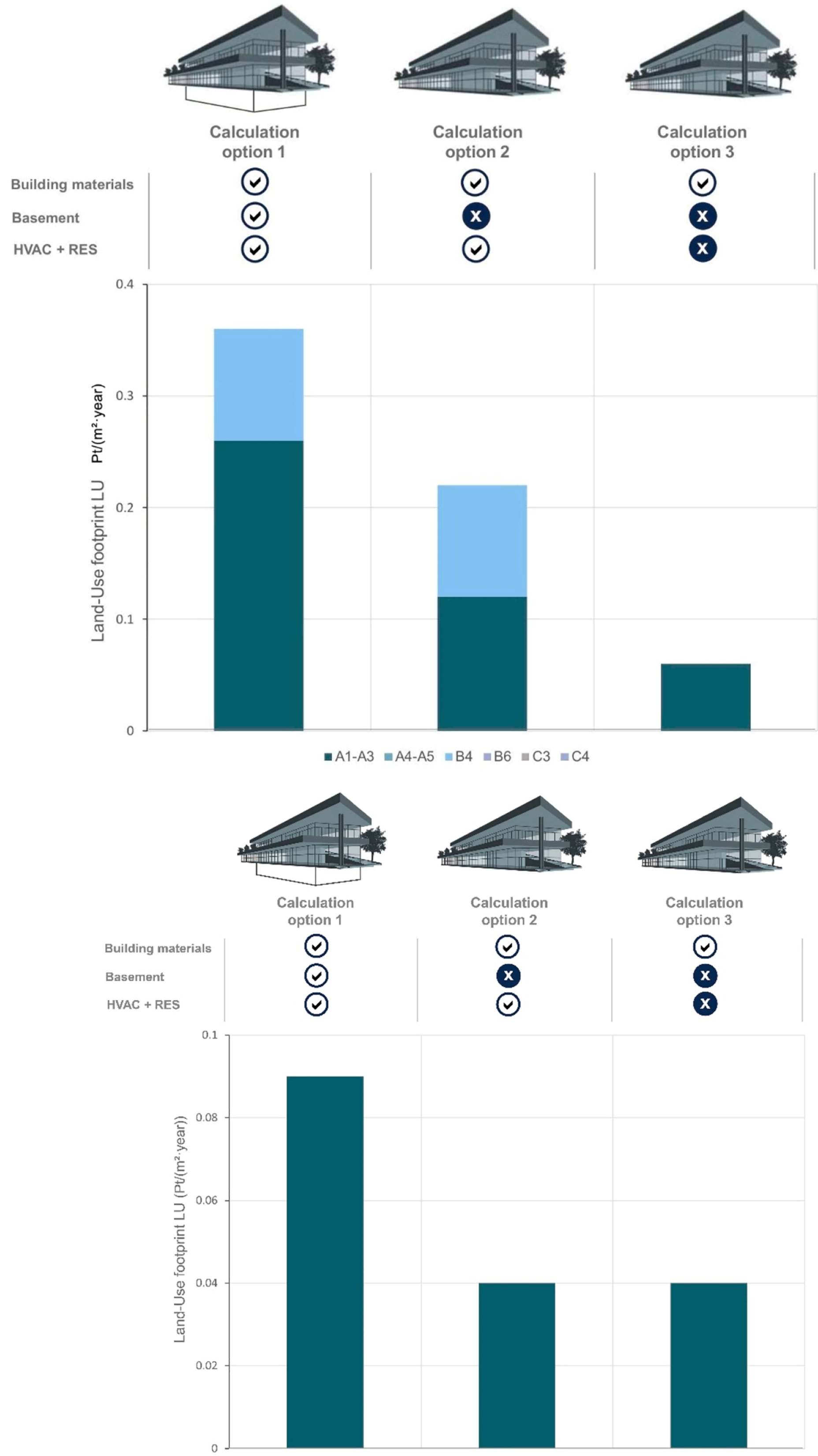

Fig. 7. Land-use (LU) footprint of the Circular Pavilion expressed in Pt/(m²·year), calculated using the EF 3.1 (LANCA) Soil Quality Index for built-up land occupation in the Netherlands.

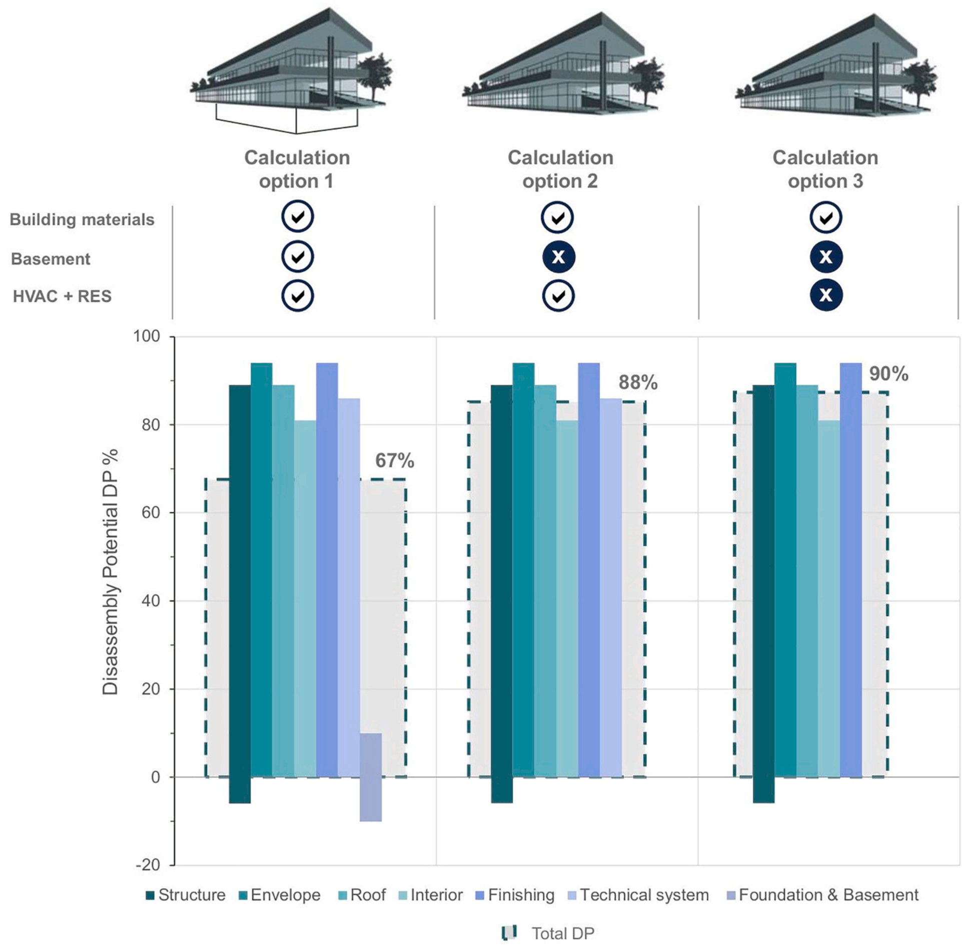

Fig. 8. Disassembly potential scores for case study components. Negative values result from the penalty system applied in the DeCon tool, indicating that irreversible or destructive connections (e.g., adhesives, cast-in-place joints) outweigh reversible connections. Values below zero should be interpreted as negligible disassembly potential.

integration of reused components.

Fig. 11 presents a visual representation of BCEF, illustrating a comprehensive comparison between the three calculation options in radar format based on the framework's KPIs. This radar chart summarizes the relative behavior of the six BCEF indicators across the three calculation options under the study's stated scope and normalization assumptions. The visualization is intended to support comparative interpretation between internally consistent design scopes rather than to claim an absolute "percent circularity." Higher DP, RC, FA, and PSS scores combined with lower GWP and LU values indicate stronger circular-design integration within BCEF's indicator set, but these patterns remain conditional on the selected system boundaries, the availability of project-specific data, and the chosen normalization bounds [16–22]. To improve interpretability, the radar is accompanied by an explicit reading scale that distinguishes between (i) quantitative LCIA-based indicators (GWP, LU), aligned with EN 15804+A2 and EN 15978 [20,21], and (ii) percentage-based circularity indicators (RC, DP, FA, PSS), informed by ISO 20887 and prior circularity frameworks [27–42]. The purpose of the figure is therefore to make trade-offs and hotspots visible at early design stage, not to establish a benchmark against "typical practice" or against other circularity tools in this single-case demonstration.

Based on the radar scores, Options 2 and 3 yield higher BCEF index values than Option 1 because they intentionally exclude or de-emphasize low-recoverability, high-mass elements (notably basement concrete) and focus on above-ground assemblies and components with clearer pathways for disassembly and reuse. Importantly, these results should be interpreted as a within-case scope comparison rather than a comparison against a "conventional office baseline," since no external counterfactual building was modeled in this study [16,30]. Option 1 therefore functions as the internal baseline (full-building scope) against which the two design scopes (above-ground and optimized circularity scope) are compared. In this case, the main driver of the difference is the basement and foundation system, which increases GWP and LU while reducing DP and FA due to the practical irreversibility of heavy concrete substructures, as also observed in circular deconstruction literature [25,87]. The result demonstrates BCEF's sensitivity to design scope and recoverability assumptions, which is precisely the type of early-stage insight the framework is designed to surface [17].

5.8. Sensitivity analysis

A quantitative sensitivity analysis was conducted to evaluate the robustness of BCEF to weight perturbations under the current aggregation model (min–max normalization and weighted sum), consistent with practices reported in prior circularity assessment studies [16,37]. Each of the six KPI weights was perturbed by ±10 % while preserving a total sum of 1.0 via compensatory adjustments, and the recalculation was performed for all three options. This analysis tests parametric sensitivity of the composite score to weight choices, but it does not quantify (i) uncertainty in the underlying inventory data, (ii) uncertainty in normalization bounds, or (iii) structural uncertainty associated with

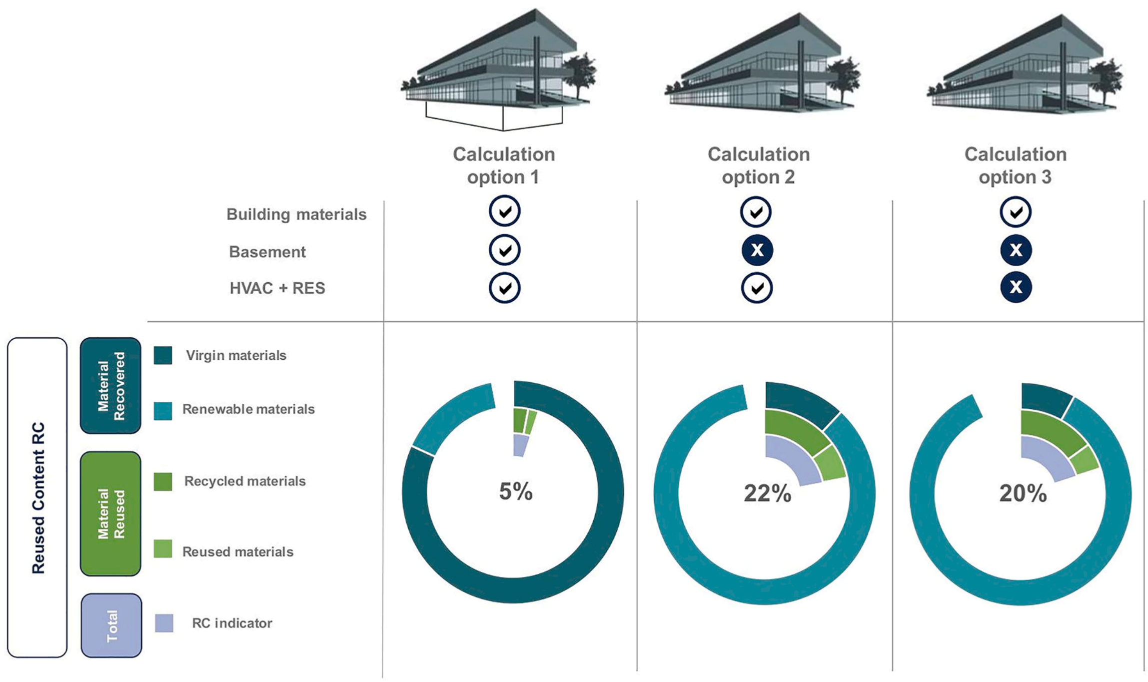

Fig. 9. Reused content results of the Circl pavilion.

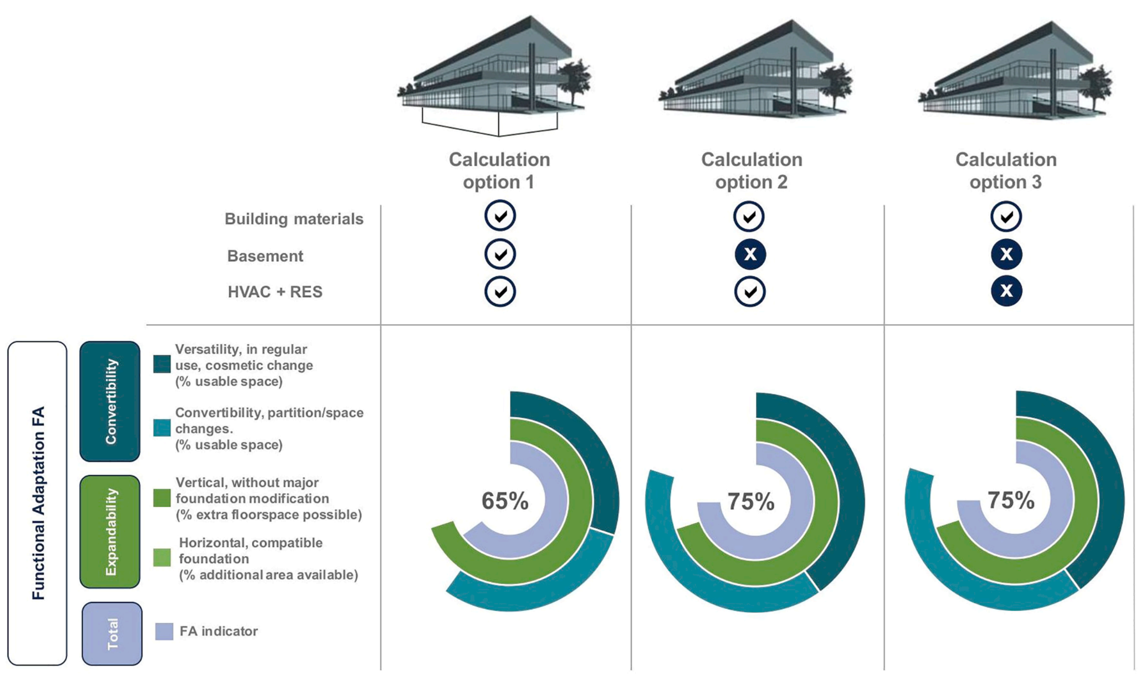

Fig. 10. Functional adaptation results of the Circl pavilion.

alternative aggregation models, as discussed in CE-LCA and multi-criteria assessment literature [17,22]. The resulting BCEF ranges, therefore, indicate how strongly the index depends on stakeholder preference encoded as weights, not the probabilistic uncertainty of the building's "true" circularity. The observed spreads across the three options confirm that results are weight-sensitive, especially where GWP is traded against RC and PSS, which supports the methodological recommendation that BCEF be used with transparent weight reporting and, where needed, scenario-specific or stakeholder-specific weight sets [37, 88].

The results, summarized in Appendix 7, indicate varying degrees of sensitivity across the three options. Calculation Option 1 (full-building baseline) exhibited BCEF values ranging from 45.35 % to 61.75 %, a spread of 16.4 percentage points. Option 2 (above-ground scenario) demonstrated greater fluctuation, with BCEF values spanning from 57.15 % to 72.75 % (a range of 15.6 points). Calculation Option 3 (optimized circularity scenario) demonstrated the highest sensitivity, with BCEF values ranging from 59.9 % to 76.1 %, representing a 16.2-point range.

The most impactful shifts occurred under the following

Table 5
PSS in the Circl pavilion compared with the optimal reference case.

Category	Weight	Product-Service Systems PSS					
		Optimal reference case			ABN AMRO Circl pavilion		
		Incl/ Discl	Number	Score	Incl/ Discl	Number	Score
Furniture	1	✓	2	2	✓	1	1
System	2	✓	5	10	✓	3	6
Partition & Finish	3	✓	1	3	×	0	0
Shell	4	✓	5	20	×	0	0
Core	5	✓	3	15	×	0	0
			Total score	**50**		**Total score**	**7**
				Overall total / 50			**7**
				Overall total %			**14**

perturbations:

- +10 % GWP, −10 % RC, and +10 % GWP, −10 % PSS led to the highest BCEF scores across all options, indicating GWP's strong positive influence on the composite score when prioritized.
- Conversely, +10 % RC, −10 % GWP, and +10 % PSS, −10 % GWP resulted in lower composite scores, suggesting a comparatively weaker influence of RC and PSS when increased at the expense of GWP.

These results reveal that Calculation Option 3 is the most responsive to changes in weight distribution, reflecting its reliance on design-optimized circular features that interact more directly with dynamic weighting. Option 2 shows similar sensitivity, while Option 1, representing a less optimized baseline, demonstrates comparatively reduced responsiveness, likely due to the dominant impact of its foundational mass.

Overall, the analysis confirms that BCEF is sensitive to weight assumptions, particularly for GWP, RC, and PSS. This highlights the need for transparent weighting protocols and potentially context-specific

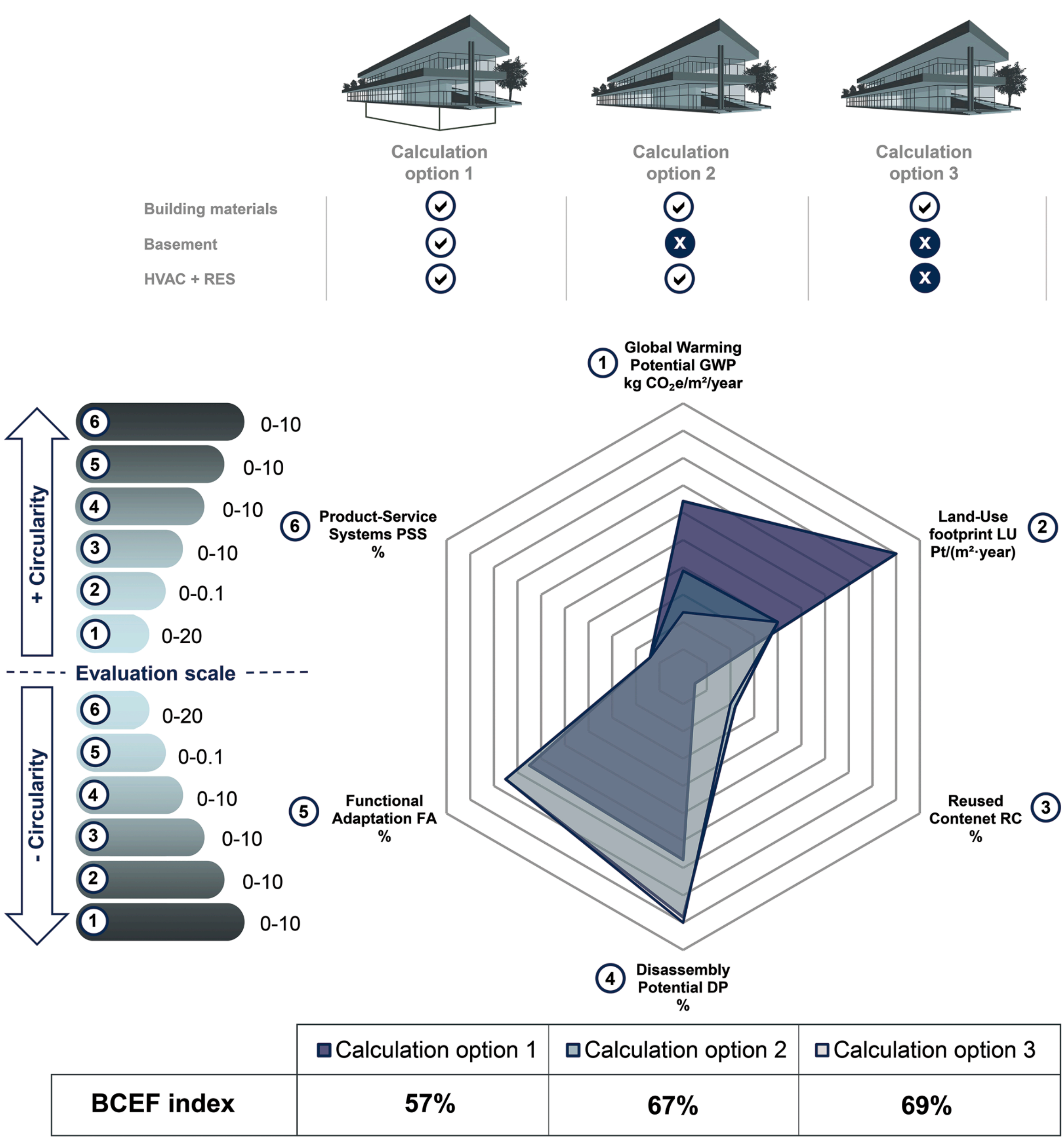

Fig. 11. Radar chart illustrating the Building Circularity Evaluation Framework (BCEF) results across six key performance indicators (KPIs) for the three calculation options of the Circular Pavilion.

adjustments depending on project goals or regulatory priorities. Future refinements could include stakeholder-based weight elicitation or probabilistic weighting schemes to further enhance framework reliability and applicability across diverse building typologies.

6. Discussion

6.1. Summary and main findings

The Circl Pavilion is an information-rich and deliberately circular showcase project, and its selection was intentional to test BCEF under conditions where disassembly and reuse strategies are explicit and documented [78,79]. This choice strengthens internal coherence testing (indicator behavior, module mapping, and scoring transparency), but it limits external validity: the resulting BCEF values should not be interpreted as representative of typical office buildings or general practice [16,30]. Accordingly, the contribution of this paper is methodological demonstration and internal stress-testing of BCEF, not statistical generalization. The three calculation options were defined to expose how scope decisions (full-building vs above-ground vs disassembly-optimized components) influence indicator outcomes and the composite score, thereby highlighting where circularity performance is most affected by design choices and recoverability assumptions, consistent with observations in whole-building circularity research [27,31].

Application of BCEF to the three options shows that the composite score is driven by a small number of dominant mechanisms: (i) mass-intensive, low-reversibility substructure elements that penalize GWP and LU and constrain DP and FA, and (ii) recoverable above-ground assemblies and reused components that raise DP and RC. This aligns with broader findings in whole-building circularity assessment, which emphasize the critical role of system boundaries and recoverability assumptions [16–87]. In contrast to circularity-only scoring approaches such as WBCI or BCI, BCEF intentionally couples circular design proxies (DP, RC, FA, PSS) with LCIA-based pressures (GWP, LU) in a single, transparent structure, enabling early-stage visualization of trade-offs rather than isolated optimization [17,22]. At the same time, the present study does not claim superiority over other frameworks through comparative experiments; instead, it demonstrates that BCEF can be executed with explicit module mapping, normalized indicator scoring, and clear scope options, producing interpretable differences that are actionable for early design discussion [30,37]. The early disassembly of the project after seven years further underscores the importance of evaluating adaptability, reversibility, and scope-dependent reuse potential rather than assuming planned service life translates into realized circular outcomes [79].

1. Difficulty in Removing Bolts from Structural Connections. The first issue arises from the difficulty in unscrewing the bolts used in the building's structural connections. In some cases, bolts and even portions of wooden connections had to be cut because of their resistance to disassembly.
2. Challenges with the Concrete Basement Structure. The second issue pertains to reinforced concrete basements. Before the deconstruction, a 3D scanning system was used to survey the entire basement. Subsequently, a specialized demolition company was hired to cut the reinforced concrete into specific dimensions because full dismantling was deemed unfeasible, as mentioned in Section 5.3.
3. Groundwater Pressure on the Basement. The third challenge involves groundwater pressure acting on the basement. As the aboveground components were dismantled, the load on the basement structure decreased, causing the buoyant force of the groundwater to lift the concrete basement upward. Many concrete blocks were placed to counteract buoyancy, allowing all above-ground components to be fully dismantled and mitigating this issue during the deconstruction process.

These challenges significantly delay the deconstruction process. Fig. 12 shows a part of the disassembly process during a site visit.

Regarding functional adaptation, the results were similar across all calculation options due to the use of open and adaptable spaces, except for certain internal concrete walls in the basement, which had a significant impact on the building's circularity indicator. The application of PSS in BCEF highlights the feasibility of service-oriented models, which shift the focus from product ownership to service provision. However, introducing the PSS indicator into BCEF is a step toward refining the assessment frameworks for the circular economy. While its current performance may be limited, its significance lies in its potential to catalyze the broader adoption of circular economic practices. By fostering transparency and accountability, a PSS model can significantly influence the evolution of sustainable business practices and ultimately drive systemic changes in the near future. The Circl pavilion demonstrates that even modest advancements in PSS metrics can offer valuable insights and inspire greater commitment to circularity. As such, this initiative represents a practical implementation and foundational experiment that can inform the global trajectory of circular economy strategies.

Therefore, we recommend standardization efforts in the construction industry. The case study demonstrates the need for standardized circular product information to enhance industry-wide adoption and ensure consistency in circularity assessments. Additionally, circularity indicators should be designed to support and integrate into future European and international standards, fostering greater comparability and reliability across projects. By refining the Building Circularity Evaluation Framework (BCEF) to align with these evolving standards, the construction sector can adopt a more unified and effective approach to measuring and enhancing circularity.

6.2. Strengths and limitations of this research

The BCEF significantly aids decision-making during the early stages of the design process. Its strength lies in its ability to inform designers about the feasibility of a design before finalizing decisions and to facilitate comparisons across different calculation options. A key advantage is its use of KPIs derived from a comprehensive literature review, enabling scalable application across varying levels of input detail and frameworks. The integration of Building Circularity Indicators (BCIs) with life cycle impact assessment (LCIA) distinguishes BCEF by encompassing the full life cycle, from material production to end-of-life.

BCEF further consolidates existing knowledge, incorporates standardized indicators, and aligns with regulatory requirements such as those from CEN/TC 350. Among existing frameworks, DGNB, BREEAM, Level(s), and Madaster each address circularity partially: they lack early-stage engineering applicability, integrated cross-indicator weighting, or explicit connection-level disassembly assessment. BCEF is the first framework to combine all three within a single, digitally operable, standards-aligned structure. The application of the DeCon expert system for semi-automated disassembly scoring, validated against a real building deconstruction, provides an engineering-grade evidence base not present in prior circularity frameworks. This positions BCEF as a reproducible, quantitative engineering tool adaptable to future policy and design environments.

The observation that Option 1 received the lowest circularity score (53 %) is not merely a numerical outcome but a validation checkpoint for the BCEF framework. This design option featured a basement-intensive layout with irreversible connections and heavy material use, which in practice led to significant challenges in material recovery during deconstruction. The BCEF accurately captured this limitation through low disassembly and reuse scores, confirming its capacity to reflect real-world circularity constraints. This alignment supports the construct validity of the method and underscores its utility as a predictive tool during early design stages. Rather than highlighting the

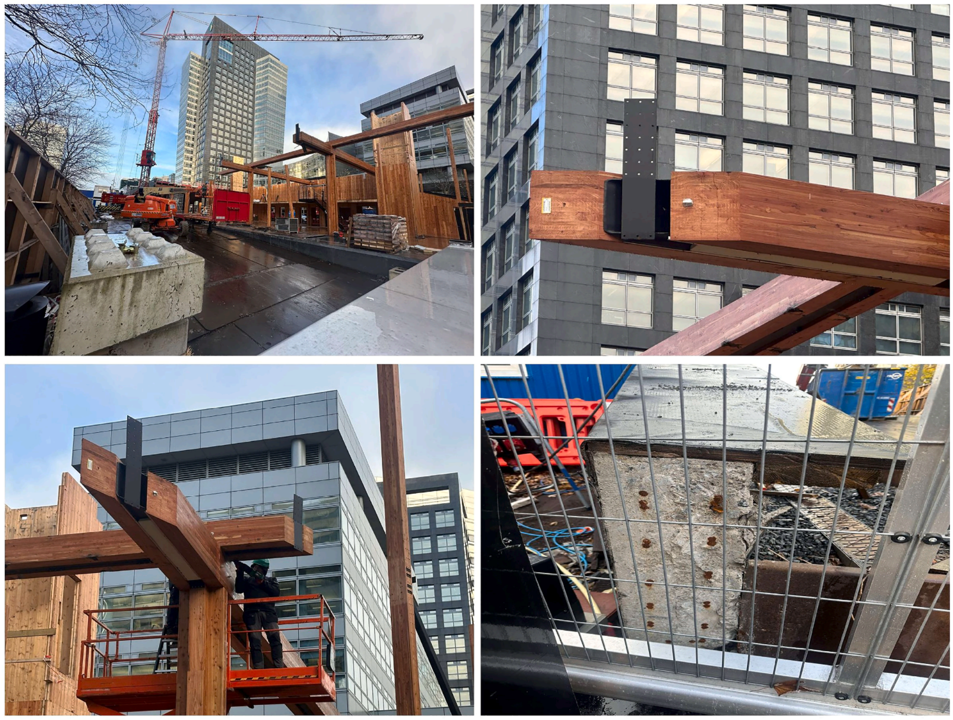

Fig. 12. The Circl pavilion during the disassembly process.

result in isolation, this case illustrates the framework's broader diagnostic value in identifying structural and material features that compromise circular performance.

Similarly, Option 3 received high disassembly and reuse scores, reflecting its modular design and efficient separation of the service layer. These scores aligned with empirical observations, reinforcing the reliability of the framework's disassembly and reuse indicators. The stability of scenario rankings under ±10 % changes in indicator weights demonstrates internal consistency and robustness.

Therefore, BCEF provides predictive potential by allowing early-stage comparisons of design options and estimating likely performance trends across circularity and life cycle impact indicators. Existing frameworks and rating systems such as LEVEL(s), Madaster, and DGNB tend to focus narrowly on either operational impacts or digital inventory management, often excluding system-oriented indicators like Functional Adaptation (FA) and Product-Service Systems (PSS). BCEF's integration of these underrepresented indicators offers a more holistic perspective, particularly valuable in early-stage design. The radar-based visualization format facilitates intuitive multi-criteria decision-making, improving usability compared to score-heavy systems.

Nonetheless, limitations persist. BCEF currently emphasizes material mass for assessing reused content, which may skew results toward heavier materials (e.g., concrete) and undervalue lighter but high-impact systems (e.g., HVAC, PV). While material mass was used as the primary quantification basis due to data availability and compatibility with LCA tools, it may overrepresent components that are heavy but not functionally dominant, such as PV panels. These panels contribute minimally to functional circularity (e.g., adaptability or reuse potential), and their inclusion was maintained solely to ensure consistency across indicators (e.g., the impact of energy systems under PSS or operational GWP) [89]. Future iterations of the BCEF should consider alternative normalization strategies, such as economic value, embodied energy, or functional utility, to address this bias. Future iterations could incorporate composite weighting schemes reflecting mass, embodied carbon, and service life.

Furthermore, while BCEF aligns with EN 15804+A2 and ISO 20887, broader validation across diverse building typologies, project scales, and climatic contexts is essential to assess the external generalizability of the findings. Benchmarking against established frameworks and applying BCEF across longitudinal case studies could further enhance its reliability and acceptance.

6.3. Future work and possible applications

The Building Circularity Evaluation Framework (BCEF) represents a significant step toward operationalizing circularity assessment during the early design stages of buildings. While the current version of the framework integrates six key performance indicators (KPIs), it intentionally excludes certain dimensions, such as water use, toxicity, and social sustainability, which remain underdeveloped or contested within the scope of circular economy (CE) definitions. Future research may incorporate these aspects as data availability and consensus on their quantification improve.

BCEF complements ongoing European standardization efforts, notably the emerging CEN/TC 350 framework on Circular Economy in the Construction Sector – Framework, Principles, and Definitions [7]. Annex B of this standard proposes new circularity indicators, including Resource Flow Analysis (RFA), the Material Circularity Indicator (MCI), and Construction Waste Diversion Rates (CWDR). These indicators enrich the understanding of material efficiency and waste dynamics across the building life cycle. However, their integration at early design stages remains methodologically and practically challenging due to limited predictive capability. BCEF addresses this gap by focusing on operational, design-phase-compatible metrics that can directly support early decision-making and stakeholder engagement.

To enhance its relevance and future applicability, BCEF is well-positioned to align with upcoming EU policy instruments, most notably:

- The EU Digital Product Passport (DPP), mandated under the revised EcoDesign for Sustainable Products Regulation (ESPR), will require construction products to disclose key sustainability and circularity data, including information on material composition, recyclability,

repairability, and reusability. BCEF's structure, particularly its Disassembly Potential (DP), Reused Content (RC), and Product-Service Systems (PSS) indicators, could be adapted to inform DPP data layers, especially those relating to end-of-life value retention and component traceability. Integration with DPP would also enhance the transferability of BCEF outputs into digital building logbooks, BIM object libraries, and procurement platforms.
- The Energy Performance of Buildings Directive (EPBD) Recast (2024/1275): For the first time, the EPBD requires Member States to assess and report whole life cycle Global Warming Potential (GWP) of buildings. BCEF already incorporates GWP as a core KPI, aligned with EN 15978 and EN 15804+A2. By extending BCEF to include Module D impacts and aligning its GWP indicator with national LCA databases (e.g., TOTEM, ÖKOBAUDAT), the framework could contribute directly to EPBD reporting and compliance monitoring.

Moreover, BCEF supports convergence with other instruments such as the LEVEL(s) framework, the Construction Products Regulation (CPR), and upcoming EU Taxonomy Delegated Acts on circularity. Integration of these frameworks would enable BCEF to serve not only as a design support framework but also as a compliance and certification mechanism.

To maintain scientific robustness and practical relevance, future development of BCEF should consider:

- Incorporating dynamic weighting systems based on stakeholder priorities or project typologies.
- Testing with probabilistic or Monte Carlo methods for uncertainty quantification.
- Adding support for automated data extraction from BIM and material passports.
- Refining indicators to better reflect circular procurement strategies and contractual models (e.g., leasing or take-back schemes).

The practical utility of BCEF depends on its broad validation across building types and stakeholder profiles. While the Circl Pavilion provides a unique case of disassembly and reuse, future case studies should target additional typologies, such as residential, educational, and healthcare, to stress-test the framework's flexibility. This could be supported by usability testing with architects, engineers, and contractors to assess its integration into typical workflows and procurement stages [40].

The framework's alignment with CEN/TC 350′s new SC1/WG5 working group, focused on developing technical guidance for circularity assessment, provides a platform for institutionalizing BCEF principles into future European norms. Active participation in this working group will enable the authors to contribute to the development of standardized approaches for indicator selection, data reporting, and aggregation methodologies.

Ultimately, BCEF has the potential to support a new generation of digital and regulatory tools for circular construction. Its application to the Circl Pavilion sets a benchmark by demonstrating how post-disassembly data, service-based procurement models, and modular design can be jointly assessed within a unified framework. Compared to existing frameworks such as LEVEL(s), BCI, or TOTEM, BCEF bridges the gap between theoretical modeling and actionable circular design.

The growing portfolio of built examples, such as the Lister Building (Brussels) and CBCI Living Lab (Ghent), reflects increasing readiness to adopt performance-based circularity indicators. BCEF can serve as a harmonizing instrument to guide these practices across design stages, stakeholder groups, and regulatory contexts, enabling early-stage trade-off analysis between circularity, carbon, and adaptability.

Through broader validation, policy alignment, and digital integration, BCEF can evolve into a mainstream assessment and benchmarking framework that not only reflects the state of the art but actively shapes the future of circular construction in Europe and beyond.

7. Conclusion

The Building Circularity Evaluation Framework (BCEF) provides a structured and transparent whole-building evaluation approach that operationalizes six indicators, Global Warming Potential, Land-Use Footprint, Reused Content, Disassembly Potential, Functional Adaptation, and Product-Service Systems, in a single early-stage assessment workflow. The contribution is not the invention of new indicators, but the explicit integration of indicator scope definition, life-cycle module mapping, normalization, weighting, and aggregation into a reproducible evaluation structure aligned with EN 15804+A2, EN 15978, and ISO 20887 [20–42].

Demonstration on the dismantled Circl Pavilion shows that BCEF can be applied to a real project with documented circular features and can differentiate outcomes across three scope definitions (full-building, above-ground, and disassembly-optimized component scope) [78,79]. However, this single-case demonstration does not establish generalizable benchmarks or external validity, and it does not replace comparative testing against conventional baselines or other assessment tools [16,30]. The results should therefore be interpreted as evidence of feasibility, transparency, and internal consistency, with clear limitations regarding representativeness.

Future work should focus on (i) expanding testing to additional building typologies and to at least one explicit counterfactual baseline per typology, (ii) formalizing indicator selection and weighting protocols (for example, structured elicitation and consistency checks), and (iii) extending sensitivity treatment beyond weights to include uncertainty in inventory data, normalization bounds, and alternative aggregation models, as recommended in recent reviews of circularity metrics and CE-LCA methods [17–88]. These steps are required before BCEF can be used for benchmarking claims; they are also necessary to make BCEF robust for policy-facing use cases and for integration into digital workflows such as BIM-linked material passports, Digital Product Passports, and procurement decision support [31,52].

Dear Sir,

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Muheeb Al-Obaidy: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luc Courard:** Writing – review & editing, Supervision. **Rafael Passarelli:** Writing – review & editing, Supervision. **Enola Giannasi:** Software, Investigation, Formal analysis, Data curation. **Shady Attia:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2026.110824.

Appendices

The full list of technical appendices, detailed tables, and consultation reports referenced in this paper is available in the companion report: Al-Obaidy, M., & Attia, S. (2025). Development of the BCEF and DeCon Tools. Université de Liège. ISBN 978-2-930909-25-7. Retrieved from https://orbi.uliege.be/handle/2268/334554

Data availability

https://orbi.uliege.be/handle/2268/334554

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