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Fragmentation to Harmonisation: An Empirical Comparison of Circularity Assessment Methods in Modular and Conventional Building Retrofits

A comparison of four circularity performance assessments applied in a modular over-cladding system versus conventional retrofit case, examining method distinctives, diversity and fragmentation – identifying pathways toward harmonisation.

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ABSTRACT

The transition from linear to circular economy models in construction has led to the rapid development of circularity assessment methods; however, substantial fragmentation persists due to divergent definitions, indicators, system boundaries, and temporal frameworks. While previous studies have systematically reviewed these methods, limited empirical research compares methods and performance when applied to practice based identical building cases.

This study addresses this gap through a controlled comparative analysis of four circularity assessment approaches applied to two functionally equivalent façade retrofit systems: a conventional adhesive-bonded external wall insulation (EWI) system and a prefabricated modular system designed for disassembly. The methods include a simplified circularity / Design-for-Disassembly (DfD) assessment, the STaMPD hierarchical DfD framework, the Whole Building Circularity Indicator (WBCI) with Life Cycle Assessment (LCA), and a combined single and multi-cycle LCA approach with supplementary DfD evaluation.

Results show consistent convergence in identifying the modular system as superior in circularity performance, confirming that fundamental design features, such as reversible connections and functional independence, are robustly detected. However, significant divergence in outcomes arises from differences in indicator selection, weighting, hierarchy, and temporal framing. Single-lifecycle LCA indicates substantially higher upfront embodied carbon for the specific modular system case (+82%), highlighting a key tension between particular circular reversible design and short-term carbon targets. Multi-cycle LCA accounted for re-use enabled by disassembly but remains sensitive to allocation methods and future reuse assumptions.

The study demonstrates that methodological choices fundamentally influence circularity assessment outcomes and proposes a harmonisation framework comprising core indicators, hierarchical structure, and a tiered assessment approach.

1. Introduction

1.1. Research Background

The construction sector exerts significant pressure on natural resources and the environment, consuming approximately 3 billion tons of raw materials annually [1] and generating 37.5% of the European Union's total waste [2]. This resource intensity and waste proliferation largely result from linear economy models characterised by "take-make-waste" processes [3]. Less than 1% of existing buildings are estimated to be fully demountable [4], leading to approximately 1 billion tonnes of construction and demolition waste (CDW) disposed to landfill annually [5], despite 57% of materials retaining reapplication potential at end-of-life [6].

Circular economy (CE) principles have emerged as a paradigm shift from linear models toward regenerative systems that retain resources, minimise waste, and enable material reintegration at end-of-life [7]. CE is defined as "an industrial system that is restorative or regenerative by intention and design," founded on three core principles: i) elimination of waste and pollution, ii) circulation of products and materials, and iii) regeneration of natural systems [3]. Within the built environment, circularity is increasingly recognised as essential for sustainability, prompting growing research into strategies, frameworks, and solutions [8, 9].

As CE gains prominence in construction, numerous assessment tools and frameworks have been developed to evaluate circularity performance. Kirchherr *et al*., (2017) identified 114 CE definitions in literature [10], Saidani *et al*., (2019) classified 55 circularity indicators [11], and Parchomenko *et al*., (2019) documented 63 metrics [12]. In the built environment, assessment approaches vary widely: material-focused indicators such as Material Circularity Indicator [13]; building-level frameworks - Building Circularity Indicators [14, 15]; Design for Disassembly (DfD) assessments [16-18], and hybrid frameworks integrating lifecycle assessment with circularity metrics [19, 20].

Lifecycle Assessment (LCA) is one of the most widely used tools for evaluating environmental impacts in the built environment [21, 22], standardised under ISO 14044:2006, EN 15978:2011, and EN 15804+A2:2019. However, LCA applications for circularity face limitations: existing standards were developed under a linear paradigm, focusing predominantly on single-lifecycle assessments from cradle-to-grave [23, 24], inadequately addressing circular lifecycles, DfD benefits, and multi-cycle material reuse [25, 26]. Despite the proliferation of assessment approaches, no industry-standarised circularity assessment exists for the built environment, with comprehensive whole-building methods identified as a key knowledge gap [27-31].

1.2. Problem Statement

Fragmentation in circularity assessment manifests across five critical dimensions:

i) Definitional Diversity

No single standardised definition of circularity exists in the built environment. Conceptualisations range from narrow recycling-focused interpretations to holistic perspectives encompassing biological and technical cycles, value retention hierarchies, and regenerative principles [5, 10, 32]. This ambiguity directly influences assessment design e.g. narrow definitions focusing on recycling lead to fundamentally different evaluation frameworks than broader CE approaches [33].

ii) Scope and Boundaries

Assessment scope and system boundaries vary widely, including construction hierarchies (building, system, element, component, material), lifecycle stages (production, construction, use, end-of-life, multiple lifecycles), and circularity aspects evaluated (material flows, DfD, or integrated assessment [15]. Some methods focus exclusively on technical Design for Disassembly (DfD) indicators (connections, accessibility) [16, 18], while others incorporate material, process and data aspects [17]. This scope variability limits comparability and risks omitting key circularity dimensions [28, 34].

iii) Indicator Divergence

Circularity indicators span multiple domains, including material flows, technical design, process requirements, and information systems. However, different methods select distinct subsets and combinations, reflecting underlying assumptions about what constitutes circularity [11, 12]. This divergence prevents robust benchmarking and complicates cross-study comparison [33].

iv) Hierarchical Treatment

Circularity principles emphasise value retention at the highest possible level [35], but many assessments operate at a single analytical level, overlooking differences between element reuse, component disassembly, and material re-use. This flattening of hierarchy can distort evaluation outcomes and obscure higher-value circular strategies. [27, 36, 37].

v) Temporal Framing

Circular economy principles inherently involve multiple lifecycles; however, most assessments adopt single-lifecycle perspectives, particularly within conventional LCA frameworks [21-23]. This creates systemic bias as designs optimised for long-term reuse may appear less favourable due to higher upfront material requirements supporting reversibility [24, 25]. While multi-cycle LCA approaches exist (100:0 cut-off, Linear Degressive, Circular Footprint Formula), no consensus standardises the most representative allocation method [26, 35, 38].

Collectively these fragmentation dimensions produce critical consequences: results from different studies cannot be meaningfully compared [28, 33], narrow-scope assessments may overstate circularity while overlooking weaknesses [27, 29] contradictions between circularity and environmental assessments leave designers and clients without guidance [26, 34] and policymakers lack robust, standardised metrics to support incentives and regulations [39, 40].

1.3. Research Aim and Objectives

To address this fragmentation the research positions itself at the intersection of circularity assessment, design evaluation, and lifecycle analysis, seeking to clarify how methodological differences influence both assessment outcomes and decision-making in practice.

While existing studies have systematically reviewed circularity indicators and assessment frameworks, these analyses are predominantly conceptual or comparative at the methodological level. There remains a limited body of empirical research applying multiple circularity assessment methods to identical practice-based construction cases under controlled conditions. Consequently, the extent to which methodological differences influence assessment outcomes, design interpretation, or effect policy implications remains a research problem.

This study addresses this gap through a controlled, empirical comparison of four distinct circularity and lifecycle assessment approaches applied to functionally equivalent retrofit systems, earthing the study in case practice. By holding design variables constant, the research isolates the influence of assessment methodology, enabling direct evaluation of how differences in scope, indicators, hierarchy, weighting, and temporal framing affect conclusions regarding circularity and environmental performance. This represents a novel contribution by providing grounded evidence-based insight into method-driven divergence and the implications for circularity design performance and assessment harmonisation.

i) Research Aim

The aim of this research is to identify and critically evaluate the distinct characteristics of circularity assessment methods, and to elucidate sources of methodological fragmentation through empirical comparison, to support consideration of harmonised approaches that enable robust, comparable, and decision-relevant circularity assessment in the built environment.

ii) Research Objectives

- To empirically compare four distinct circularity and LCA-based assessment methods applied to conventional and modular façade retrofit systems under controlled conditions;
- To identify the methodological factors that most strongly influence assessment outcomes, including indicator selection, weighting, hierarchical treatment, and temporal framing;
- To examine the relationship between circularity performance and environmental impact, with particular focus on the interaction between single and multi-cycle lifecycle assessment;
- To propose a harmonisation framework that balances standardisation and comparability with flexibility across design stages, data availability, and stakeholder needs.

2. Literature Review

2.1. Circular Economy and Circularity in Construction

i) Definitions and Interpretations of Circularity

Circular economy (CE) represents a shift from linear "extract-produce-dispose" models to regenerative systems in which resources circulate continuously. The Ellen MacArthur Foundation defines CE as “an industrial system that is restorative or regenerative by intention and design,” based on three principles: elimination of waste and pollution, circulation of products and materials, and regeneration of natural systems [3, 32]. CE distinguishes between biological cycles, renewable and biodegradable materials returning to Earth, and technical cycles, where materials are retained through reuse, repair, and recycling, with value retention prioritized via cascading R-hierarchies: refuse and reduce rank highest, followed by reuse and repair, with recycling and recovery considered lower-value strategies [41].

Despite growing interest, no standardised definition exists in the built environment. Kirchherr *et al*., (2017) identified 114 CE definitions, highlighting conceptual diversity [10]. In construction, Ossio *et al*., (2023) identified five clusters in 316 publications: R-Framework/strategies (28%), CDW management (29%), building design approaches (17%), business models/networks, and lifecycle assessment (19%) [6]. Holistic definitions consider all lifecycle stages and closed-loop practices [41] while Kubbinga, (2018) define circular buildings as developed, used, and reused without unnecessary resource depletion, with demountable technical elements and biological elements returning to cycles [42].

This definitional ambiguity directly affects assessment methods. Narrow definitions focused on recycling produce material flow-centric methods [13, 14]. Jiang *et al*., (2022) notes design-focused definitions produce DfD-centric frameworks [16, 17], and holistic definitions support integrated multi-dimensional approaches [15, 19, 28]. The proliferation of assessment methods reflects this underlying definitional fragmentation [11, 12, 32].

The diversity of definitions identified in the literature directly underpins the first dimension of fragmentation examined in this study, definitional diversity. These differing conceptualisations of circularity form the basis for subsequent variation in scope, indicator selection, and assessment logic, which are systematically analysed through the comparative framework developed in Section 3.

ii) Hierarchical Scales and Value Retention

Circularity in construction operates across multiple hierarchical scales. Lei *et al*., 2021 classify CE assessment at macro (national/city), meso (industrial estate/symbiosis), and micro (product/building) levels [21]. Within micro-level organize indicators into system, component, and material sub-levels. Hierarchical understanding is critical: CE principles prioritise retaining materials at their highest utility level [21, 35], with element-level reuse (whole-system recovery) valued over component-level disassembly, and material-level recycling valued lowest.

Brand’s 6S layers model conceptualises buildings as interlinked layers with differing lifespans—Site (eternal), Structure (30–300 years), Skin (20 years), Services (7–15 years), Space (3–30 years), and Stuff (<1 year) [43, 44]. This framework supports circularity by enabling separation and removal of materials for reuse or recycling, allowing differing lifespans without affecting primary assemblies. The 6S model informs end-of-life assessments and design decisions [45].

Many methods fail to recognise hierarchy; single-level approaches (material-only or product-only) ignore that recovering a complete wall panel retains more value than disassembling into materials. Daly (2023) critiques simplified assessments for neglecting differential utility, highlighting the need for multi-level evaluation with weighting that prioritises higher-level recovery [27].

These varying approaches to hierarchical scale are directly reflected in the 'hierarchy treatment' dimension of the comparative framework used in this research, which evaluates the extent to which methods recognise and prioritise value retention across element, component, and material levels

2.2. Circularity Assessment Methods and Tools

i) Systematic Reviews of Assessment Methods

Systematic reviews highlight the diversity and fragmentation of circularity assessment approaches. Saidani *et al*. (2019) identified 55 indicators, categorizing them by assessment level, circularity dimension, lifecycle stage, indicator type, and purpose. They found 80% focused on material flows, with few addressing energy (15%), water (3%), or labor/economic dimensions (2%), and only 12% incorporated end-of-life considerations [11].

Parchomenko *et al*. (2019) reviewed 63 CE metrics, identifying three types: material flow metrics, lifecycle-based metrics, and composite indices. Fragmentation in system boundaries, functional units, and aggregation methods limits benchmarking and policy relevance [12].

Harris *et al*. (2020) reviewed 135 CE indicator studies, noting micro-level tools rarely link circularity to environmental outcomes via LCA, risking "circularity for circularity's sake" [33].

Khadim *et al*. (2022) reviewed 35 built environment tools, finding most indicators assess material flows, with some considering DfD, Design for Adaptability, and Design for Reuse. Diversity in selection exists, but common categories enable harmonisation: Technical/Systems, Material, and Process/Data. The Whole Building Circularity Indicator (WBCI) scored highest in comprehensiveness, though no method excelled across all criteria [15].

Gasparri *et al*. (2023) identified three fragmented approaches: material-centric, design-centric, and lifecycle-centric, reflecting disciplinary origins and stakeholder needs. Harmonisation requires identifying core elements while retaining context-specific flexibility [28].

While these reviews provide comprehensive classification and critique of circularity assessment methods, they are predominantly conceptual in nature. As such, they do not systematically evaluate how different methods perform when applied to identical practice-based construction cases, a gap that this study addresses through controlled empirical comparison.

ii) Material Flow Indicators

The Material Circularity Indicator (MCI) evaluates virgin input, unrecoverable waste, and utility factors, suitable for material-level assessment but limited for complex systems and early-stage design [13, 21].

Verberne (2016) adapted MCI for buildings via the Building Circularity Indicator (BCI), connecting material, product, and system levels [14]. Van Vliet (2018) enhanced BCI with 25 indicators across technical, process, and financial categories [45]. Khadim *et al*. (2023) developed the WBCI with four-level hierarchy, LCA integration, bio-based material accounting, comprehensive DfD, and normalization flexibility [15]. Despite high scoring (92/132 points), critiques remain regarding mass-dependency, lack of scarcity weighting, static residual value assumptions, and insufficient R-strategy differentiation [19, 46, 47].

iii) Design for Disassembly (DfD) Frameworks

Durmisevic (2006) developed 17 DfD indicators in functional, technical, and physical categories, emphasizing functional separation, assembly/disassembly sequences, connection types, and lifecycle coordination [16]. Durmisevic *et al*. (2019) classify strategies: design-for-reuse (highest value), design-for-reconfiguring, and design-for-recycling (lowest value) [48]. Connection typologies and edge geometry critically influence DfD performance; mechanical fixings are preferred over bonding. Guy & Ciarimboli (2007) extend DfD to 25+ factors including material and process indicators [17]. ISO 20887:2020 provides international DfD standards across five hierarchical levels: system, element, component, sub-component, and material [18].

iv) LCA Integration and Multi-Cycle Assessment

LCA standards (ISO 14040/44:2006; EN 15978:2011; EN 15804+A2:2019) quantify environmental impacts across building lifecycles. However, LCA often fails to capture circularity comprehensively, focusing on limited indicators such as recycling and reuse rates [21]. Module D of EN 15978 allows inclusion of reuse, recycling, and energy recovery, but is often excluded and considers only single lifecycles. De Wolf *et al*. (2020) recommend including embedded use value, reusability, design complexity, and durability, which are generally omitted [49].

Multi-cycle LCA approaches address these limitations. Eberhardt *et al*. (2020) proposed allocation methods: 100:0 cut-off, Linear Degressive, and Circular Economy Linear Degressive [25]. Van Gulck *et al*. (2022) proposed transformation modelling for adaptation scenarios [35]. No consensus exists on best allocation, and method choice significantly affects environmental payoff timing [24, 26].

Across these approaches, variation in indicator selection, system boundaries, hierarchy, and temporal framing reflects the broader fragmentation. These methodological differences are not merely technical but fundamentally influence how circularity performance is interpreted and quantified

2.3. Identified Gaps and Research Positioning

Despite method proliferation, few studies empirically compare multiple approaches applied to identical construction cases. Most literature compares methods conceptually [11, 12, 15] or critiques prior methods during new development [15, 19, 45]. Empirical case-based comparisons are scarce, particularly for retrofit/facade systems [22] and integrated assessments linking circularity with environmental performance.

LCA standards were developed within a linear paradigm, often focusing on single lifecycles and inadequately capturing DfD and multi-cycle reuse [23-26]. This can bias assessments, making circular designs with high upfront material intensity appear inferior.

There remains a lack of empirical studies that apply multiple circularity assessment methods to the same building system under controlled conditions, limiting understanding of how methodological choices influence outcomes.

Furthermore, limited research has examined the interaction between circularity assessment and lifecycle environmental performance within a unified analytical framework.

This study addresses these gaps by applying four distinct methods to identical retrofit cases, enabling direct comparison of methodological effects across the fragmentation dimensions of definition, scope, hierarchy, indicators, and temporal framing.

3. Research Methodology and Case Study

3.1. Research Design and Analytical Approach

This study employs a comparative multi-method case study approach, applying four circularity and LCA assessment methods to two façade retrofit systems within an Irish demonstration project. The research design explicitly seeks to isolate methodological effects by holding the case constant while varying assessment methods, thereby enabling attribution of differences in results to methodology rather than design variables.

The approach responds directly to the identified gap in empirical comparison of circularity assessment methods (Section 2.3), moving beyond conceptual comparison to controlled application in practice. The research combines quantitative assessment (material flow quantification, embodied carbon calculation, lifecycle impact analysis, scoring matrices) with qualitative synthesis (method characteristics, indicator rationale, conceptual framing) and comparative evaluation across multiple analytical dimensions (scope, hierarchy, weighting, temporal framing, and outputs).

Analytical techniques include:

- Parallel application: All four methods are applied consistently to both retrofit systems using the same material data, functional performance requirements, and geographic context;
- Dimensional comparison: Methods are systematically compared across defined dimensions (Section 3.2), enabling identification of convergence (consistent findings) and divergence (contradictory or variable outcomes);
- Thematic analysis: Conceptual differences between material-centric, design-centric, and systems-centric approaches are identified and interpreted;
- Topic-based synthesis: Cross-method comparison focuses on key themes, including hierarchy recognition, temporal framing, weighting mechanisms, and LCA integration.

While the case study approach limits generalisability, its strength lies in enabling in-depth, controlled comparison of methodological behaviour under real-world conditions, providing robust insight into fragmentation and harmonisation potential.

3.2. Comparative Analysis Framework

The four assessment methods are evaluated using a structured comparative framework, developed to reflect the key fragmentation dimensions identified in Section 1.2. The framework enables systematic, like-for-like comparison across methods by applying consistent analytical criteria.

Circularity definition: Material-centric (flows/recycling), design-centric (DfD strategies), or systems-centric (holistic CE principles).

Scope and scale: Construction hierarchies (building, system, element, component, material), circularity dimensions (material flows, DfD, material properties, process, data), and breadth vs. depth.

Indicators: Number, type (quantitative/qualitative/semi-quantitative), alignment with circularity definition, measurability, data availability.

Hierarchy treatment: Levels assessed, indicator application at all levels, differential weighting to prioritize higher-level recovery, alignment with value retention principles.

Weighting mechanisms: Mass-based, energy/carbon-based, equal, category-specific, hierarchical, R-strategy-based; rationale and impact on results.

Temporal framing: Single vs. multi-cycle, lifecycle stages included (production, construction, use, end-of-life, Module D), time horizon (50–150 years), treatment of future scenarios and uncertainty.

Life stage coverage: Production (A1–A3), transport (A4), construction (A5), use stage replacement (B4–B5), end-of-life (C1–C4), Module D inclusion.

Design stage suitability: Concept (RIBA Stage 1–2), detailed (Stage 3–4), technical (Stage 5), post-construction evaluation, data requirements.

Data requirements: Sources (EPDs, generic databases, visual inspection, professional judgment), input volume, assessment time, data gaps, quality.

Materiality considerations: Bio-based materials, virgin vs. recycled vs. renewable content, biological vs. technical cycles, scarcity, toxicity.

Bespoke method dimensions (Method 4): Allocation method rationale, transformation scenario modelling, uncertainty handling, integration of DfD and material assessment.

3.3. Case Selection Rationale

The case context is an Irish demonstration project piloting a modular circular wall system in the deep energy retrofit of two partially retrofitted 1970's semi de-thatched two-story social houses of traditional masonry and timber construction, under the EU Drive 0 Project (2020-2023) [50].

The project includes the development and application of a prefabricated modular over-cladding wall system incorporating circular design principles, including Design for Disassembly (DfD), material separability, and reversible connections. This system is compared with a conventional external wall insulation (EWI) system, representing a typical linear construction approach.

The modular system was adapted from an existing light gauge steel structural wall frame to function as a prefabricated, closed cell, wall panel incorporating circularity and DfD principles. The study contrasted conventional (adhesive-bonded, irreversible) versus circular (mechanically fixed, demountable) systems to evaluate how methods distinguish linear and circular design strategies. Fig. (**1**) showing conventional and proposed system adapted system and Fig. (**2**) showing pre and post retrofit front elevations.

Retrofit provides a critical context for circularity assessment due to its scale, regulatory drivers (EU Renovation Wave and revised EPBD minimum energy performance standards) [51], and material intensity, with retrofit being an identified circularity gap [22]. As façade systems correspond to the "Skin" layer in Brand's 6S framework, their relatively short service life and high replacement frequency make them particularly relevant for circular design strategies.

The controlled comparison of conventional and modular systems enables direct evaluation of how assessment methods differentiate between linear and circular design approaches under equivalent functional conditions.

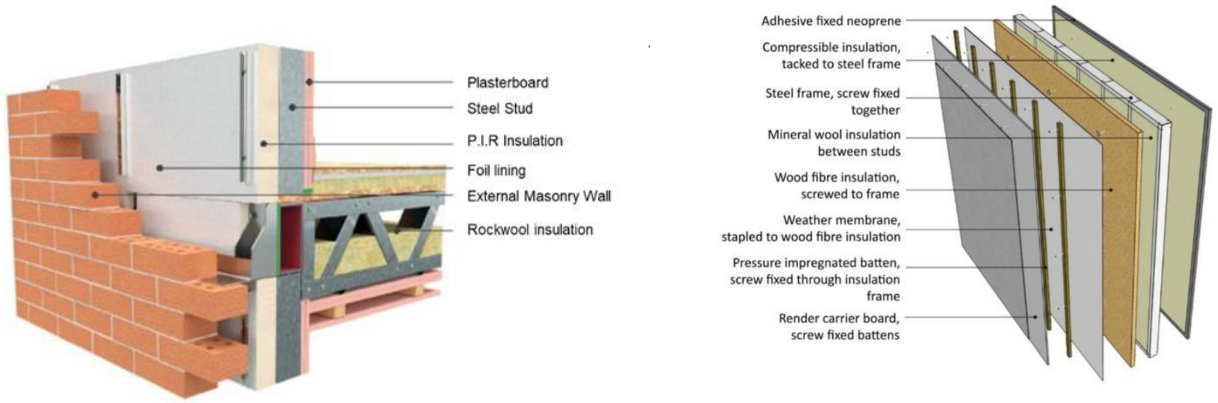


Figure 1: Showing (LHS) conventional LGS system and (RHS) proposed Irish Drive 0 modular – circular biobased system.

3.4. Case Constructions

This modular wall panel was compared to a conventional EWI system to exemplify the contrast between a modular and circular designed system to a conventional high embodied energy / carbon plastic based with poor disassembly and EOL options. These were applied to an existing masonry cavity wall host construction toward achieving a combined target wall U value 0f circa 0.18 W/m²K.

Figure 2: Showing (RHS) pre works elevation with (LHS) completed modular retrofit.

Case 1: Conventional External Wall Insulation (EWI)

- Characterised by integrated layers with limited disassembly potential.
- 160 mm EPS insulation, adhesive-bonded
- Render base coat with embedded mesh, acrylic finish coat
- U-value: 0.176 W/m²K
- 4-layer bonded system, mass: 26 kg/m², volume: 0.12 m³/m²

Case 2: Modular Circular Panel

Characterised by several layers, framing, increased mass and DfD enabled.

- LGSF frame, 89 mm studs, with options of biobased fibre insulation batts or mineral wool batts modelled in different LCA studies.
- 25 mm internal + 40 mm external wood fibre insulation, breather membrane, timber battens, cement board, acrylic render
- Mechanical bracket fixing; integral factory-installed windows
- U-value: 0.182 W/m²K
- 10-layer demountable system; mass: 39.7 kg/m², volume: 0.18 m³/m²

Both systems achieve equivalent thermal performance (U-values circa 0.18 W/m²K), ensuring functional equivalence and enabling comparison based on circularity and environmental performance rather than thermal efficiency differences.

3.5. Circularity / DfD Assessment Methods Overview

Four assessment methods were selected to represent diverse methodological approaches to circularity evaluation, spanning simplified, detailed, material flow-based, and lifecycle-integrated approaches.

These methods were chosen to capture variation in scope, hierarchy, indicator complexity, and temporal framing, thereby enabling comprehensive analysis of fragmentation dimensions.

Study 1: Drive 0 Simplified Assessment

The circularity assessment approaches applied with Drive 0 comprised core elements with some adaptation and variation during the course of four design stage assessments. This case represents a highly simplified method focused on DfD, embodied energy / carbon and some material aspects [27].

- Focus: DfD, embodied energy/carbon, material virginity/renewability
- Hierarchy: Single-level (material/product)
- Temporal scope: Single lifecycle
- Data: ICE database, design documentation
- Assessment time: ~1 day per system
- Limitation: Restricted scope and lack of hierarchical differentiation

Study 2: STaMPD DfD Framework

Comprehensive framework synthesised from Durmisevic (2006), Guy & Ciarimboli (2007), ISO 20887:2020, and material circularity literature 16-18]. STaMPD acronym denotes five assessment categories: Systems, Technical, Material, Process, Data. This method represents a detailed multi criterion and hierarchical DfD focused method as a core subset of Circularity performance [52].

- Comprehensive, hierarchical DfD-focused framework
- 29 indicators across Systems, Technical, Material, Process, Data
- Three-level hierarchy (element 1.0, component 0.75, material 0.5); optional category weighting
- Temporal scope: Single lifecycle, design-stage anticipation
- Data: Detailed drawings, product specs, professional judgment
- Assessment time: 2 days per system
- Limitation: Data intensity and reliance on expert judgement

The scoring within the STaMPD method was based on standardised 0–1 scoring scale, where 1.0 represents optimal DfD performance (e.g. dry, reversible, and accessible systems), 0.75 to 0.25 represent intermediate levels of performance, and 0.0 indicates poor or irreversible performance (e.g. bonded or inaccessible systems). Scoring is based on a combination of qualitative descriptors and defined criteria where available, supplemented by professional judgement at the design stage. This, given the early design stage, involved a degree of professional judgement, open to subjectivity, particularly in the qualitative evaluation of design characteristics, which was examined via comparison of two researcher scoring an average 2 % difference, with proposals to improve scoring criterion to reduce subjective opinion [51]. See Appendix 2 for details.

Study 3: Whole Building Circularity Indicator (WBCI) + LCA

This method was selected based on Khadim *et al*. 2022 representing a holistic, detailed, material flow method. The study by Kavanagh 2020 was supplemented with / compared to distinct element LCA analysis/tools, [53].

- Integration of Material Circularity Indicator (MCI) and Element Disassembly Index (EDI)
- Hierarchy: Four levels (building, system, element, material)
- LCA: OneClickLCA (EN 15978 compliant); GWP, AP, EP, ODP, POCP
- Temporal scope: Single lifecycle; Module D reported separately
- Assessment time: 2–3 days
- Limitation: Mass-based weighting, EDI only at element level

Study 4: Single / Multi-Cycle LCA + Bespoke Hierarchical Assessment

This *study focused on single and* multi-cycle LCA modelling, informed by Eberhardt *et al*. (2020), Van Gulck *et al*. (2022), and supplemented with bespoke DfD method developed for this research integrating hierarchical DfD assessment-based Drive 0 simplified methods and included a second EWI case with biobased insulation [25, 54].

- Single and Multi-cycle modelling: 3 lifecycles (50 years each, total 150)
- Allocation methods: 100:0 cut-off, Linear Degressive, CELD, Van Gulck transformation
- DfD assessment: Three-level hierarchy (element, component, material), four indicators (durability, disassembly potential, resource impact, Brand layers)
- Temporal scope: Multi-cycle with transformation scenarios
- Assessment time: 2–3 days
- Limitation: Dependence on allocation methods and long-term assumptions introduces uncertainty

Fig. (**3**) Schematic showing the four studies / methods applied to examine the two comparative cases and supplemental assessments / key interrelationships.

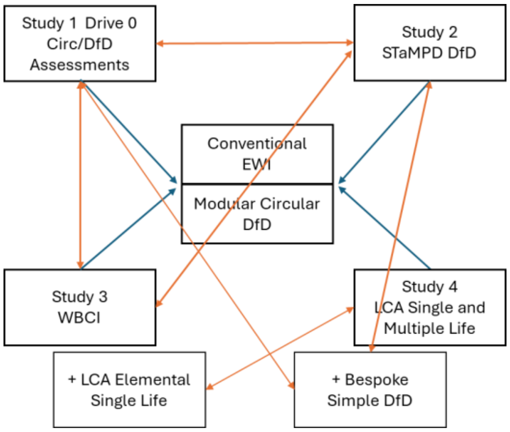


Figure 3: Schematic showing principle scope of comparison of methods to retrofit cases with supplemental methods and inter-relationships.

The four methods represent very distinct and different tools being used in circularity assessment, a simplified circularity / DfD assessment (Study 1) versus a detailed DfD hierarchical assessment method, (Study 2) versus a detailed material flow method WBCI with DfD component (Study 3) with comparative LCA assessment, versus a single and multi-life LCA assessment (Study 4) with supplemental DfD and Material assessments.

Fig. (**4**) showing schematic of three levels of modular system hierarchy, and Fig. (**5**) showing schematic construction sketches of EWI system versus Modular System – based on Drive 0.

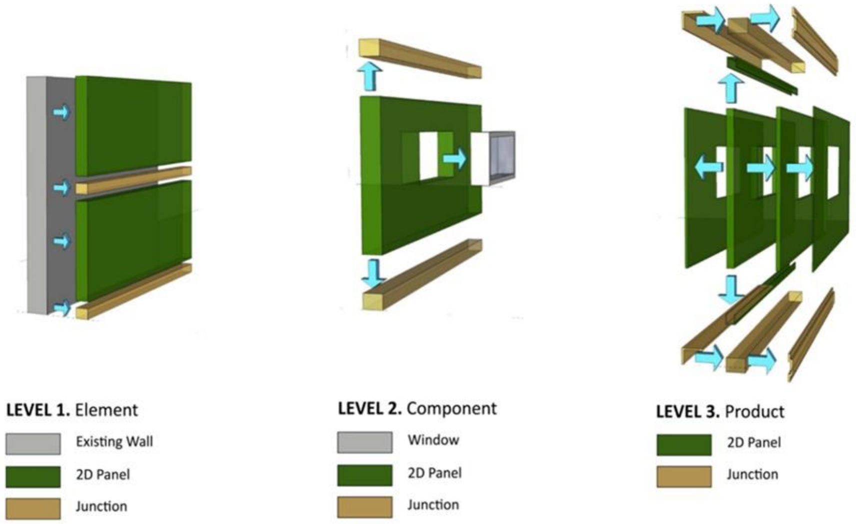
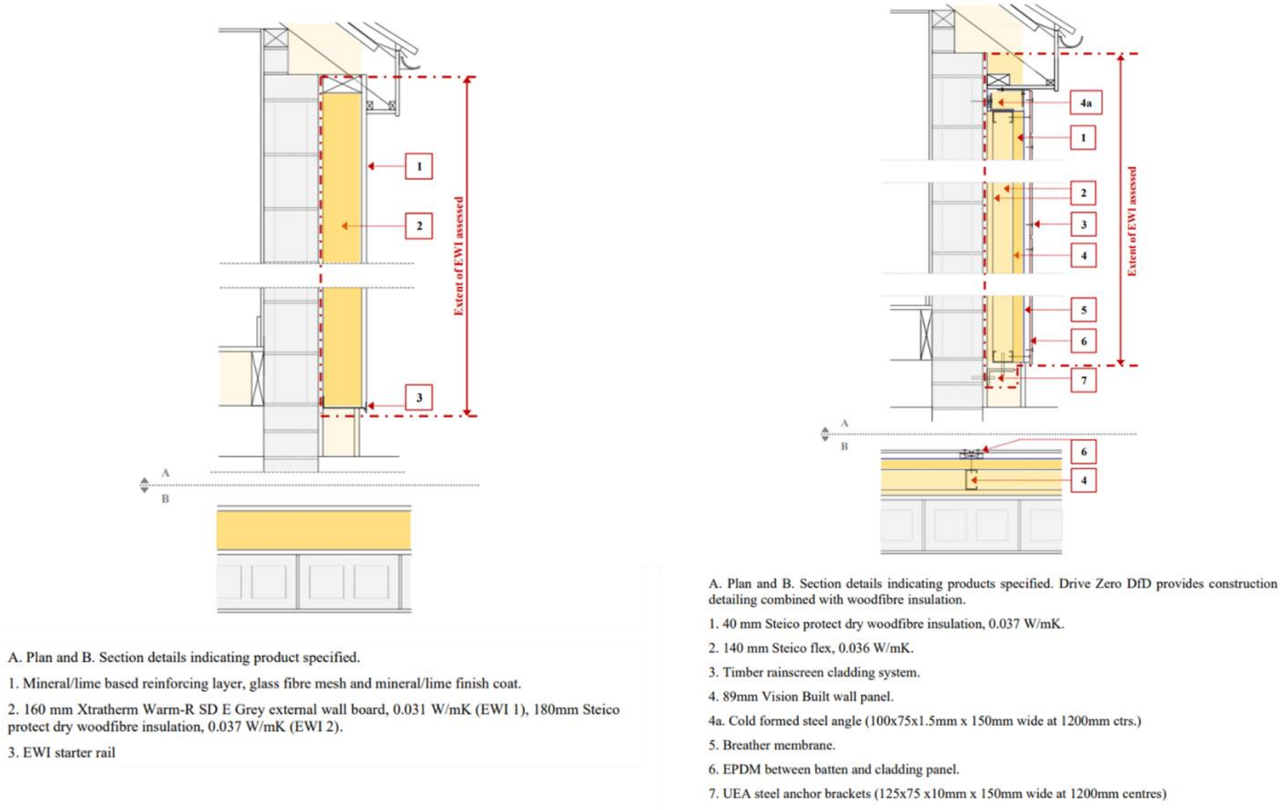


Figure 4: Modular system hierarchy. Source Drive 0 Irish demonstrator [27].



A. Plan and B. Section details indicating product specified.

1. Mineral/lime based reinforcing layer, glass fibre mesh and mineral/lime finish coat.

2. 160 mm Xtratherm Warm-R SD E Grey external wall board, 0.031 W/mK (EWI 1), 180mm Steico protect dry woodfibre insulation, 0.037 W/mK (EWI 2).

3. EWI starter rail

A. Plan and B. Section details indicating products specified. Drive Zero DfD provides construction detailing combined with woodfibre insulation.

1. 40 mm Steico protect dry woodfibre insulation, 0.037 W/mK.

2. 140 mm Steico flex, 0.036 W/mK.

3. Timber rainscreen cladding system.

4. 89mm Vision Built wall panel.

4a. Cold formed steel angle (100x75x1.5mm x 150mm wide at 1200mm ctrs.)

5. Breather membrane.

6. EPDM between batten and cladding panel.

7. UEA steel anchor brackets (125x75 x10mm x 150mm wide at 1200mm centres)

Figure 5: Showing sketch construction plan and section of LHS EWI retrofit and RHS Drive 0 Irish modular over-cladding system. Source [54].

4. Results

The primary contribution of this research is a systematic comparison of four distinct assessment methods applied to functionally equivalent construction cases, allowing for a rigorous evaluation of how each method interprets circularity, design-for-disassembly (DfD), material circularity, and environmental impact. This comparison illuminates both areas of convergence and divergence, providing insights into method sensitivity, indicator selection, and the implications of method design choices and consideration of harmonisation.

Fig. (**6**) presents a simple high level schematic overview of the focus and scope of the four studies / methods across four dimensions, circularity, design for disassembly, material focus and environmental impact.

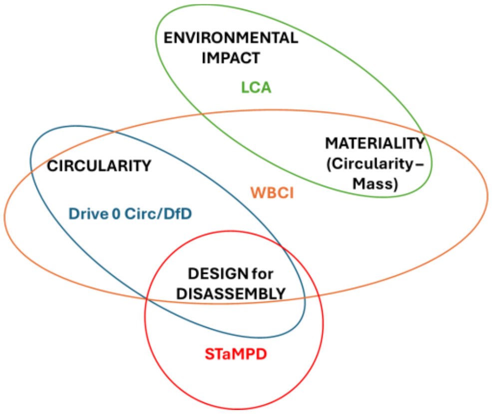


Figure 6: Schematic showing high level focus comparison for four methods, Drive 0 circularity (Blue), STaMPD (Red) WBCI (Brown) and LCA (Green).

4.1. Overall Results Comparison

Table **1** presents a comparative summary of results across the assessed metrics, including overall circularity, DfD performance, material circularity, and both single and multi-lifecycle LCA outcomes.

Across all four methods, the modular circular system consistently outperformed conventional external wall insulation (EWI) systems in circularity, DfD, and material circularity. This convergence confirms that fundamental design differences—including reversible mechanical assembly, accessible connections, functional independence, and high bio-based material content—are detectable irrespective of assessment methodology. However, the magnitude of the advantage varies substantially, reflecting differences in indicator selection, weighting mechanisms, and hierarchical treatment.

Despite its circularity superiority, the modular system exhibited substantially higher upfront embodied carbon in single-lifecycle LCA. For example, Study 3 LCA reports a 6,987 kgCO_2e burden for the modular system compared with 3,845 kgCO_2e for conventional EWI (+82%). This discrepancy arises primarily from the structural LGSF frame (2,675 kgCO_2e, 42% of A1–A3 stages) and the increased number of construction layers (10 layers vs. 4 in conventional EWI). Consequently, there exists a structural tension between circular design objectives and single-lifecycle carbon minimization.

Across all methods, the type of connection emerged as the single most influential determinant of circularity. Conventional EWI relies on irreversible adhesive bonding, consistently scoring between 0 and 0.25 out of 1.0 because non-destructive disassembly is impossible. In contrast, modular circular systems employ reversible mechanical screw fixings, achieving scores between 0.75 and 1.0 regardless of the assessment method.

Table 1: Studies 1-4 circularity assessment results summary.

Metric	Study / Method	EWI	Modular Circular	Δ Difference	Δ %
Overall Circularity	1. Drive 0 Simplified (Assess 2)	Qualitative: Low (0.51)	Qualitative: High (0.75)	+0.24	+47%
	2. N/A	–	–	–	–
	3. WBCI (SCI)	0.28	0.68	+0.40	+143%
	4. N/A	–	–	–	–
Design for Disassembly (DfD)	1. Drive 0 Simplified (Assess 2)	0.385 / 1.0	0.8275 / 1.0	+0.4425	+114%
	2. STaMPD Element	48.7 / 100	74.6 / 100	+25.9	+53%
	3. WBCI (EDI)	0.44	0.73	+0.29	+66%
	4. Bespoke DfD Element	27 / 100	68 / 100	+41	+151%
Material Circularity	1. Drive 0 (Assess 2)	0.10	0.44	+0.34	+340%
	2. N/A	–	–	–	–
	3. WBCI (MCI)	0.640	0.789	+0.149	+23%
	4. OCLCA Material Circularity Tool (Single Life)	1% (Worst)	75% (Best)	–	+74%
LCA – Single Life	3. LCA GWP A–C (Wall Elements)	3845 kg CO_2e	6987 kg CO_2e	+3142	+82%
	4. WLCA A–D – EC	15241 kg CO_2e	16363 kg CO_2e	+1122	+7.36%
	4. WLCA A–D – Total WLC (Excl. D)	57088 kg CO_2e	58307 kg CO_2e	+1219	+2.13%
LCA – Multi-Cycle 3 Methods (3 Life Cycles)	4. WLCA A–D – Baseline Avg (Incl. D)	6513 kg CO_2e	5125 kg CO_2e	−1388	−21%
	4. WLCA A–D – 100:0 Avg (Incl. D)	6513 kg CO_2e	3579 kg CO_2e	−2934	−45%
	4. WLCA A–D – LD (Incl. D)	6580 kg CO_2e	3579 kg CO_2e	-3001	-45%

Accessibility further reinforces performance differences. Fixings in conventional EWI are embedded within render layers and require destructive removal, limiting accessibility scores to approximately 0.25 out of 1.0. Modular systems locate fixings at panel perimeters within dedicated access zones, enabling disassembly and yielding accessibility scores of approximately 0.75. While some intermediate fixings require partial disassembly, intentional design for access significantly amplifies the benefits of reversible connections.

Functional independence differentiates the systems further. Conventional EWI layers are chemically and physically integrated, preventing separation without destruction and resulting in low scores (~0.25). Modular panels are structurally independent and can be demounted as complete units, achieving the maximum score of 1.0, thereby enabling high-value recovery pathways.

Material composition is another significant differentiator. Conventional EWI uses 100% virgin, fossil-based materials, with negligible potential for reuse or recycling. Modular systems incorporate approximately 86–90% bio-based content, including timber and woodfibre, allowing for complete reuse or energy recovery via incineration. The weighting of bio-based content varies by method and is accounted different across methods: WBCI heavily rewards it, Drive 0 circularity underweights it, and LCA accounts for biogenic carbon sequestration.

Recovery hierarchy influences assessment outcomes. Conventional EWI offers no element-level recovery; disassembly requires material destruction. Modular systems facilitate recovery at multiple levels: entire panels can be reused, components such as windows can be separated, and individual materials can be recycled. Methods that explicitly consider hierarchical recovery therefore favour modular systems more strongly than single-level approaches.

Allocation method selection in multi-cycle LCA determines when environmental benefits of circular design are realized. The modular system achieves environmental advantage in life one under CELD allocation, life two under Linear Degressive (LD), and life three under 100:0 allocation. Van Gulck modelling demonstrates that modular systems can replace outer layers independently (timber cladding, battens, render) without full material replacement, providing early environmental payoff.

It should be noted that this observed increase in upfront embodied carbon is highly case-specific, driven by use of a light-gauge steel frame and increased layer complexity; alternative modular systems, in comparison to a highly simple three layer non reversible EWI system. Other strategies such as used of timber framing or biobased materials, or simplified assemblies, may exhibit substantially different carbon–circularity trade-offs, and therefore this result should not be generalised across all circular construction systems. Rather it highlights a design tension and caution concerning how disassembly is integrated in construction systems.

4.2. Dimensional Cross Method Analysis

Table **2** summarises the principal differences between the four assessment methods across fourteen analytical dimensions. Rather than reiterating these attributes, the following analysis focuses on the key interpretive insights emerging from their comparative application, particularly in relation to fragmentation and method-driven variation in results.

The comparison demonstrates that differences in assessment outcomes are not solely a function of system performance but are fundamentally shaped by the underlying methodological framework, including how circularity is defined, the scope and scale of analysis, and the treatment of hierarchy and time. These variations influence not only the magnitude of circularity scores but also the interpretation of design performance and environmental implications.

A primary source of divergence lies in how circularity is conceptualised. Material-centric approaches, such as WBCI, prioritise quantitative material flows and therefore strongly reward bio-based content and recycled inputs. In contrast, design-centric frameworks such as STaMPD emphasise disassembly potential, where connection reversibility and accessibility are dominant determinants.

Table 2: Dimensional cross-method comparison.

Dimension	Study 1 Drive 0 Simplified	Study 2 STaMPD DfD Framework	Study 3 WBCI + LCA	Study 4 LCA Multi-Cycle + Bespoke
1. Circularity Definition	Implicit: DfD connections + embodied impacts	Holistic: physical, material, process & data integration (ISO 20887 influence)	Material flows + DfD; Ellen MacArthur MCI + Durmisevic factors	Dual: DfD hierarchy for value retention + material sourcing & end-of-life biological/technical cycles
2. Scope & Scale	Element/product level; technical DfD + embodied carbon/materials; narrow	Element/component/material; systems, technical, material, process, data; comprehensive	Building/system/element/material; material flows + technical DfD; broad	Element/component/material; DfD + material flows; moderate–broad
3. Indicators	4 DfD + 2 embodied + 3 material (9 total)	29 indicators across 5 categories	Mass-based material flow indicators + EDI (7 DfD factors)	LCA environmental indicators (e.g. GWP) + Bespoke: 4 DfD + 2 material (6 total)
4. Hierarchy	Single level (material/product)	Three levels: element 1.0, component 0.75, material 0.5	Four levels: building/system/element/material; mass-weighted aggregation	Three levels (element/component/material); material assessment separate
5. Weighting	None (separate outputs)	Volume proportioning; optional category/hierarchical weighting	Mass-based aggregation (MCI); criticised for high-volume bias	Bespoke R-strategy weighting: reuse 1.0, renewable/recycled 0.75, downcycle 0.5, virgin 0
6. Temporal Framing	Single lifecycle; initial embodied focus	Single lifecycle; design stage anticipating disassembly	WBCI single lifecycle + LCA (A–C primary), Module D separate	Multi-cycle: 3 lifecycles (~150 yrs); four allocation methods
7. Life Stage Coverage	Lifecycle implied; design focus; EOL via EE EC & materials	Lifecycle implied; EOL considered in DfD scoring	WBCI implicit; LCA A1–A3, A4–A5, B4–B5, C1–C4; Module D usually excluded	A1–A3, A4–A5, B4–B5, C1–C4, Module D integrated; transformation scenarios
8. Design Stage Suitability	Early concept → detailed design (rapid)	Detailed / technical design (data intensive)	Detailed design (EPD dependent)	Detailed design → research modelling
9. Data Required	Moderate: ICE database + visual inspection (~1 day)	High: ~179 material inputs + professional judgement (1–2 days)	High: EPDs, quantities, scenarios (2–3 days)	Moderate–high: EPDs, DfD documentation, EOL modelling (2–3 days)
10. Materiality	Limited; EE EC + added bio-based indicator (not weighted)	Minimal; mainly DfD-related (toxicity, durability, corrosion)	Moderate; bio-based in MCI (separate from recycled), toxicity in EDI	LCA includes environmental impact; Bespoke: bio-based weighted (0.75 renewable / 1.0 EOL incineration)
11. Environmental Impact	Minor focus – embodied carbon, toxicity, bio-based	Minimal – only material effects on DfD	Moderate – circularity focus (MCI)	Significant – environmental impacts via LCA
12. Primary Output	DfD scores + embodied kgCO$_2$e	Total score (0–100) + category breakdown	SCI / ECI / MCI scores (0–1), LFI, EDI + GWP stages A–C + Module D	DfD score (0–100), material circularity %, cumulative lifecycle GWP
13. Primary Strength	Fast, simple, suitable for early design	Comprehensive scope + hierarchical structure	LCA integration + standardized environmental data	Multi-cycle logic, temporal transparency, scenario modelling
14. Primary Limitation	Narrow scope, no hierarchy	Time-intensive, subjective inputs, complexity	Mass-weighting bias; Module D often excluded	Allocation choice uncertain; long-term projections speculative

Scope and analytical depth further differentiate method behaviour. Simplified approaches, such as the Drive 0 method, provide rapid assessments aligned with early design stages but inherently limit insight due to reduced indicator coverage and absence of hierarchical differentiation. In contrast, more comprehensive frameworks such as STaMPD and WBCI capture a wider range of circularity dimensions but require significantly greater data input and analytical effort. Multi-cycle LCA extends this further by incorporating future lifecycle scenarios, offering deeper temporal insight but introducing additional uncertainty.

Hierarchy emerges as a critical differentiating factor influencing results. Methods that explicitly recognise multiple levels of value retention, element, component, and material, assign greater significance to high-value recovery strategies such as whole-system reuse. Conversely, single-level approaches effectively flatten this hierarchy, potentially underestimating the benefits of modular and reversible systems.

Temporal framing is particularly influential in shaping conclusions. Single-lifecycle assessments, dominant in conventional LCA practice, prioritise upfront impacts and therefore tend to penalise material-intensive circular systems. In contrast, multi-cycle approaches capture downstream benefits associated with reuse, transformation, and recovery, resulting in fundamentally different interpretations of environmental performance over time.

These methodological differences reflect underlying disciplinary origins and stakeholder priorities. Material flow methods derive from industrial ecology, DfD frameworks from architectural and engineering practice, and LCA-based approaches from environmental assessment. As such, fragmentation is not arbitrary but arises from legitimate variations in purpose, application context, and analytical focus.

Table **2** summarises these differences across fourteen dimensions starting with foundational circularity definition, which influences scope, scale and indicators, hierarchy, weighting, temporal framing, life / design stages, data intensity, environmental impact, outputs, strengths and limitations.

Fig. (**7**) provides a high-level visual comparison of these differences using a five-point Likert scale (1 = very low/narrow; 5 = very high/comprehensive), illustrating the relative emphasis placed by each method across key dimensions. (See Appendices for scoring).

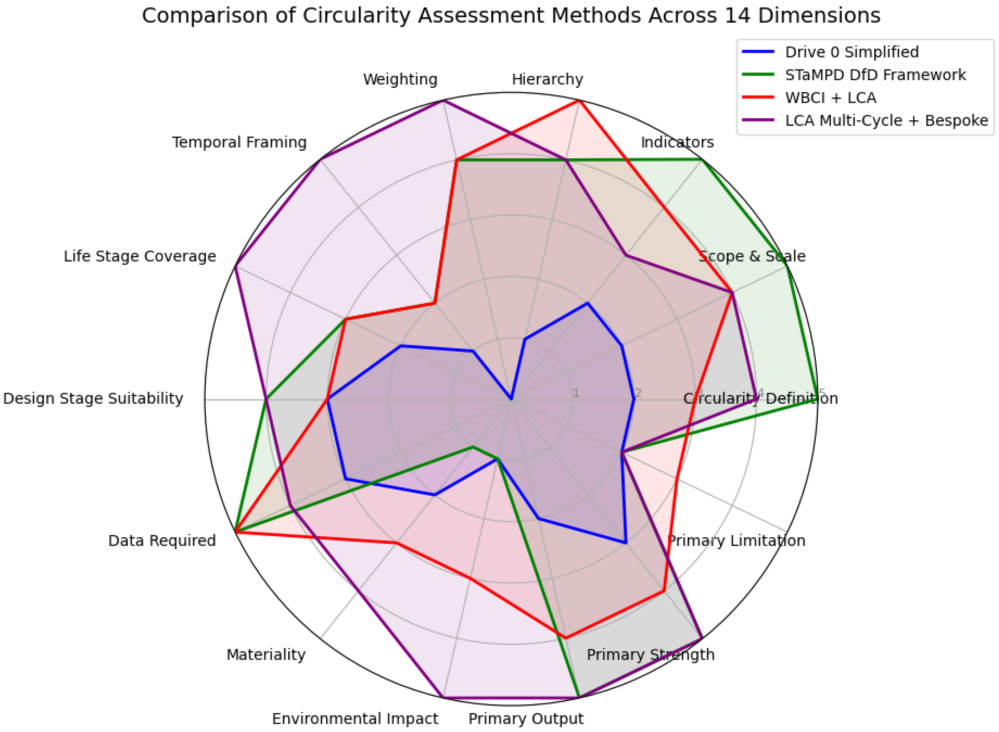


Figure 7: Showing high level radar chart comparing dimension focus for each study / method. See Appendices for scoring method and results.

5. Critical Discussion

5.1. Fragmentation

The comparative analysis demonstrates that fragmentation in circularity assessment is not merely methodological inconsistency but reflects deeper theoretical and disciplinary divergences in how circularity is conceptualised and operationalised. This finding aligns with prior literature identifying circularity assessment as a fragmented field characterised by diverse indicators, system boundaries, and conceptual frameworks [11, 15, 28].

i) Disciplinary Origins and Stakeholder Diversity

The results confirm that circularity assessment methods are strongly shaped by their disciplinary origins. Material flow-based approaches such as MCI and WBCI are grounded in industrial ecology, where emphasis is placed on quantifying resource inputs and outputs through measurable indicators. In contrast, Design for Disassembly (DfD) frameworks, including STaMPD and ISO 20887, originate from architectural and engineering practice, focusing on constructability, reversibility, and technical feasibility of disassembly. Lifecycle Assessment (LCA) methods derive from environmental science and prioritise standardisation, quantifiable environmental impact, and regulatory comparability.

This disciplinary differentiation corresponds closely with the classification of circular economy metrics into material-centric, design-centric, and lifecycle-centric categories identified by Gasparri *et al*. [28], and with the indicator diversity documented by Saidani *et al*. [11]. The empirical results of this study demonstrate that these conceptual orientations are not neutral but actively shape assessment outputs, with each method privileging particular aspects of circularity.

Stakeholder requirements further reinforce this fragmentation. Designers typically require rapid, low-data assessments suitable for early-stage decision-making, aligning with simplified tools such as Drive 0. Researchers prioritise methodological completeness and analytical rigour, as reflected in comprehensive frameworks such as STaMPD and WBCI. Policymakers favour standardised metrics, often linked to LCA, while manufacturers prefer product-level indicators. As highlighted by Khadim *et al*. (2022), this diversity in stakeholder needs contributes to the proliferation of partially aligned assessment tools rather than convergence around a single standardised method [15].

ii) Definitional Ambiguity and Indicator Divergence

The study confirms that definitional ambiguity is a primary driver of fragmentation. With over 100 definitions of circular economy identified in the literature [10], assessment methods necessarily embed different interpretations of what constitutes circular performance. Consistent with the taxonomy proposed by Saidani *et al*. (2019) [11], three dominant conceptualisations are evident:

- material-centric (resource flows and recycling efficiency)
- design-centric (DfD and adaptability)
- systems-centric (value retention across multiple lifecycles)

The empirical comparison demonstrates that these definitions result in measurable differences in outcomes, not only in the magnitude of circularity scores but also in the prioritisation of design strategies. For example, WBCI strongly rewards bio-based material content due to its material flow orientation, whereas STaMPD places greater emphasis on connection reversibility and accessibility. This confirms that indicator selection is not merely technical but reflects embedded normative assumptions about circularity, as identified in prior research [33].

iii) Circularity–LCA Tension

A central finding of this research is the tension between circularity assessment and single-lifecycle LCA outcomes. This tension reflects a structural misalignment between circular economy principles, which emphasise long-term value retention, and conventional LCA frameworks, which are typically configured around single-lifecycle system boundaries [23, 24].

The case study demonstrates that the modular circular system, while consistently outperforming the conventional system in circularity metrics, exhibits higher upfront embodied carbon under single-lifecycle assessment. This empirical finding supports concerns raised in the literature that existing LCA practice may not fully capture the benefits of circular design strategies when future reuse and recovery pathways are excluded or treated separately [25, 26].

However, it is important to recognise that this does not invalidate single-lifecycle LCA. For short-term climate targets, particularly those aligned with 2030 carbon reduction goals, upfront embodied carbon remains a critical and immediate consideration. Circular design strategies that increase material intensity may therefore present legitimate trade-offs between short-term impact and long-term benefit. Furthermore, the realisation of multi-cycle benefits depends on uncertain future conditions, including the development of reuse markets, policy frameworks, and disassembly infrastructure.

iv) Temporal Framing and Multi-Cycle Assessment

Temporal framing emerges as a decisive factor influencing assessment outcomes. Single-lifecycle assessments provide a snapshot of immediate impacts, whereas multi-cycle approaches evaluate performance across extended time horizons. This distinction reflects broader debates in lifecycle assessment regarding system boundaries and allocation methods in circular economy contexts [20, 38].

The multi-cycle LCA results in this study demonstrate that the environmental performance of circular systems improves over time, but the magnitude and timing of this improvement are highly sensitive to allocation methods and assumptions regarding reuse rates. This supports findings by Samani (2023) and Van Gulck (2022), who highlight the lack of consensus in modelling circular lifecycle scenarios and the implications for result variability [26, 35].

v) Synthesis: Fragmentation as Structural Rather than Accidental

Overall, the findings confirm that fragmentation in circularity assessment is structurally embedded rather than incidental. It arises from the interaction of:

- differing conceptual definitions of circularity
- disciplinary origins and methodological traditions
- stakeholder-specific requirements
- divergent assumptions regarding time, hierarchy, and value

This aligns with previous research indicating that methodological diversity reflects legitimate differences in analytical purpose rather than simple inconsistency [15, 28].

However, the empirical results also demonstrate that while methods converge in identifying broad trends—such as the superior circularity of modular systems—the degree of differentiation and the interpretation of environmental implications vary significantly. This reinforces the need for harmonised approaches that establish common core principles and indicators while retaining sufficient flexibility to accommodate context-specific applications.

5.2. Harmonization Framework

Harmonisation of circularity assessments is presented with the challenge of facilitating pluralism of stakeholder needs, design stage, data sets etc. in tension with the need for some standarisation for design comparison, benchmarking, planning and policy.

The harmonisation framework proposed in this study is therefore explicitly designed to balance comparability and flexibility. It seeks to establish a common core structure that enables consistent evaluation across projects and methods, while retaining sufficient adaptability to accommodate differences in design stage, data availability, and stakeholder priorities. In this way, the framework directly responds to the fragmentation identified in Section 5.1, by addressing divergences in definition, indicators, hierarchy, and temporal framing without constraining methodological diversity.

Drawing from this research a possible harmonised definition is therefore proposed:

"Circularity in construction is the degree to which buildings are designed, constructed, and managed to (1) minimise virgin resource extraction and waste generation through closed-loop material flows; (2) enable disassembly, adaptation, and reuse through design strategies; and (3) retain value at the highest possible level across multiple lifecycles within biological and technical cycles."

This definition integrates the material-centric, design-centric, and systems-centric perspectives identified in the literature and empirical analysis, providing a unifying conceptual basis for cross-method alignment.

This definition could form the basis for a core indicator set that captures material flows, DfD enablers, and hierarchical value retention.

i) Core Indicator Set

A core set of twelve indicators is proposed to enable cross-study comparability:

- Material Flows (5): Virgin material input (%), Recycled/reused content (%), Renewable/bio-based content (%), Reuse potential at end-of-life (%), Unrecoverable waste (%).
- Design for Disassembly (4): Connection reversibility, Connection accessibility, Functional independence, Edge geometry.
- Material Properties (3): Hazardous content, Durability, Standardization.
- Optional Extended Indicators: Process (fabrication, tools, complexity), Data (material passports, instructions), Systems (number of parts, relational patterns).

The adoption of a core indicator set is intended to provide a minimum common basis for assessment, addressing the indicator divergence identified in Section 5.1 while allowing extension to suit specific applications.

ii) Hierarchical Assessment and Tiered Approach

Assessment must recognise hierarchical value retention, with a minimum three-level structure: Element (1.0), Component (0.75), Material (0.5) within construction.

In addition a three-tiered framework could accommodate design stage and data availability:

Tier 1 – Rapid Screening: Core 12 indicators, element-level, single lifecycle with Module D reported separately; qualitative output <1 day; suitable for early design.

Tier 2 – Standard Assessment: Core + selected extended indicators, three-level hierarchy, product-specific EPDs, single lifecycle + Module D, quantitative score 2–3 days; suitable for detailed design and compliance.

Tier 3 – Comprehensive Assessment: Full core and extended indicators, four-level hierarchy, multi-cycle assessment with multiple allocation methods, 5+ days; suitable for research, policy development, and demonstration projects.

All tiers maintain consistent indicator definitions, allowing "upgrade" from Tier 1 to Tier 2/3 while preserving benchmarking compatibility.

This tiered structure directly addresses the tension between usability and methodological depth identified in the results (Section 4.2), enabling progressive refinement of assessment while maintaining consistency of core metrics and definitions.

5.3. Recommendations

Drawing on the comparative analysis and case study evidence, recommendations are structured across Research, Practice, and Policy to support the development and implementation of circularity assessment in the built environment.

i) Research

Validation: Pilot the harmonized framework across diverse building types to test indicator sensitivity and hierarchical scoring.

Digital Tools: Integrate assessment modules into BIM for automated data collection, scoring, and multi-cycle LCA modeling.

Longitudinal Tracking: Compare predicted versus realized circularity and environmental performance to refine single- versus multi-cycle projections.

Method Refinement: Assess sensitivity to service life, reuse rates, allocation methods, and grid carbon intensity for robust, comparable results.

ii) Practice

Designers: Apply Tier 1 for early-stage screening; aim for Tier 2 scores >70/100 in detailed design; prioritize element-level demountability and bio-based materials.

Clients/Developers: Include circularity targets alongside carbon goals; request Tier 2 assessment; accept 10–20% upfront carbon premium if multi-cycle benefits are demonstrable.

Manufacturers: Provide EPDs including Module D; design for disassembly; issue disassembly instructions and material passports; establish take-back schemes.

iii) Policy

In response to the fragmentation and methodological divergence identified in this study, policy development should adopt a phased approach that allows for capacity building, standardisation, and gradual integration into regulatory frameworks. This reflects the need to balance ambition with the practical realities of industry readiness and data availability.

Phase 1: Capacity Building (2025–2027)

- Mandate the reporting of Module D within LCA assessments to improve visibility of reuse and recovery potential
- Pilot circularity assessment requirements and targets within public procurement projects
- Develop national guidance documents and benchmarks for combined carbon–circularity assessment
- Support industry training, data infrastructure, and development of material databases and EPD availability

Phase 2: Implementation (2028–2030)

- Introduce mandatory combined carbon and circularity benchmarks within building regulations and public procurement frameworks
- Integrate harmonised circularity indicators alongside lifecycle carbon limits within national and EU-level standards (e.g. EN 15978 updates)

- Embed circularity assessment within compliance pathways, including planning, design, and certification processes
- Support the development of secondary material markets, material passport systems, and disassembly infrastructure to enable realisation of circular benefits

Long-term (2030–2050)

Require multi-cycle compliance demonstrating environmental performance over multiple lifecycles; establish fully operational material passport systems and secondary markets; and support circular economy infrastructure through policy, training, and investment.

This phased approach supports a progressive transition from voluntary adoption to mandatory integration, enabling the industry to build the necessary capacity while moving towards consistent, harmonised circularity assessment practice.

5.4. Limitations

The study has several inherent limitations:

Case-Specificity: Results reflect two Irish retrofit cases and may not generalise across all façade types, structural systems, or climatic contexts. Material intensity, layer configuration, and LGSF frame use drive specific performance outcomes.

Methodological Assumptions: Scoring of DfD indicators involves subjective judgment, despite consensus resolution; multi-cycle LCA depends on assumptions for service life (50 years base, ±30/70 sensitivity), reuse rates, and grid carbon intensity.

Data Constraints: Reliance on product-specific EPDs, generic European databases, and manufacturer data introduces uncertainty, particularly for novel or biobased materials.

Temporal Uncertainty: Multi-cycle modelling over 150 years involves inherent unpredictability; scenario-based sensitivity analysis mitigates but does not eliminate uncertainty.

Generalisability of Carbon Findings: The observed increase in upfront embodied carbon for the modular system (+82% in Study 3) is specific to the configuration analysed and should not be generalised to all circular or modular construction systems. This result is strongly influenced by the use of a light-gauge steel frame (LGSF) and the increased material intensity associated with a multi-layered assembly (10 layers compared to 4 in the conventional system). Alternative modular configurations—such as timber-based structural systems, reduced-layer assemblies, or optimised material specifications—may exhibit substantially different carbon profiles and trade-offs between circularity and embodied impact. As such, the relationship between circular design and upfront carbon is context-dependent and requires case-specific evaluation.

Despite these limitations, the study provides robust insights into method-driven fragmentation, circularity-LCA trade-offs, and practical pathways for harmonization and multi-cycle assessment.

6. Conclusions

6.1. Summary of Findings

This research provides an empirical multi-method comparison of circularity assessment approaches applied to functionally equivalent construction cases, revealing critical fragmentation that fundamentally determines assessment outcomes. Four distinct methods—simplified DfD assessment (4 indicators), comprehensive STaMPD framework (29 indicators), WBCI integrated (multi indicators) with single life LCA, and multi-cycle LCA assessment with hierarchical evaluation—were applied to conventional adhesive-bonded external wall insulation versus prefabricated modular circular retrofit in Irish residential context.

Fragmentation was confirmed across six dimensions: indicator diversity (4-29 indicators), hierarchy treatment (single to four-level), temporal framing (single-lifecycle dominance vs. multi-cycle logic), weighting mechanisms (absent, mass-based, hierarchical, R-strategy), conceptualisation (material-centric vs. design-centric vs. systems-centric), and usability (1-day rapid vs. 5-day comprehensive). Despite fragmentation, all methods consistently identified the modular system as superior in circularity performance, demonstrating that fundamental design features such as reversible connections, accessibility, and functional independence are robustly detectable across methods.

A key finding is the divergence between circularity performance and environmental outcomes in single-lifecycle assessment. The modular system exhibited higher upfront embodied carbon in single-lifecycle LCA, reflecting increased material intensity required to enable disassembly and reuse. However, single-lifecycle LCA may undervalue circular strategies under certain conditions, particularly where future reuse, recovery, and transformation benefits are excluded or treated separately. Multi-cycle LCA partially resolves this divergence, although outcomes remain sensitive to allocation methods and assumptions regarding future reuse.

6.2. Contributions

This research makes several contributions.

First, it provides a novel empirical comparison of multiple circularity assessment methods applied to identical construction cases under controlled conditions, enabling isolation of methodological effects. Second, it demonstrates how methodological design—particularly indicator selection, hierarchy, and temporal framing—directly influences assessment outcomes and interpretation. Third, it identifies and evidences the structural tension between circularity assessment and conventional lifecycle assessment approaches. Finally, it proposes a harmonisation framework comprising core indicators, hierarchical evaluation, and a tiered approach to support comparability and practical implementation.

6.3. Implications

The findings have important implications for practice, policy, and standardisation.

For practice, designers should integrate circularity assessment from early design stages and prioritise strategies enabling disassembly and reuse. For policy, there is a need to complement carbon metrics with circularity indicators to avoid unintended bias against reversible and modular systems. For standardisation, future revisions of LCA frameworks (e.g. EN 15978 and EN 15804) should consider incorporating multi-cycle assessment methodologies and harmonised circularity indicators.

6.4. Future Research

Future research should validate the proposed harmonisation framework across a wider range of building typologies, structural systems, and geographic contexts. Further work is also required to refine multi-cycle LCA methodologies, particularly regarding allocation methods, reuse scenarios, and long-term uncertainty. Integration of circularity assessment into digital design tools, such as BIM-based platforms, represents a key area for development, enabling more efficient and consistent application in practice.

Conflict of Interest

No potential conflicts of interests are reported by the author.

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Appendix 1 Scoring of Method Dimensions

Scoring for Fig. (**7**) using a six-point t scale (0 = not incorporated, 1 = very low/narrow; 5 = very high/comprehensive.

Dimension	Drive 0 Simplified	STaMPD DfD Framework	WBCI + LCA	LCA Multi-Cycle + Bespoke
Circularity Definition	2	5	3	4
Scope & Scale	2	5	4	4
Indicators	2	5	4	3
Hierarchy	1	4	5	4
Weighting	0	4	4	5
Temporal Framing	1	2	2	5
Life Stage Coverage	2	3	3	5
Design Stage Suitability	3	4	3	4
Data Required	3	5	5	4
Materiality	2	1	3	4
Environmental Impact	1	1	3	5
Primary Output	2	5	4	5
Primary Strength	3	5	4	5
Primary Limitation	2	2	3	2

Appendix 2: STaMPD Method and Scoring Summary

i) Method Overview

The STaMPD (Systems, Technical, Materials, Process, Data) method is a holistic Design for Disassembly (DfD) assessment framework for evaluating circular construction systems at early design stage. It integrates indicators from the literature into a structured, multi-level approach to support design optimisation and benchmarking.

The framework distinguishes between:

- Core physical factors (“what” is disassembled):
  Systems, Technical, Materials
- Enabling factors (“how” disassembly occurs):
  Process, Data

A total of 29 harmonised indicators are organised across these five categories, including:

- Systems: standardisation, geometry, functional independence, number/relationship of parts
- Technical: connection type, edge condition, accessibility, tolerance
- Materials: durability, toxicity, composition, number of materials
- Process: fabrication, transport, assembly, tools, safety, skills, complexity, time
- Data: construction, material, and disassembly information

Assessment is undertaken across three hierarchical levels:

1. Element (e.g. wall system)
2. Component (e.g. panel)
3. Product/Material

This hierarchical structure enables multi-scale evaluation and identification of performance variation, particularly in relation to value retention at higher levels.

ii) Scoring Method

Each indicator is assessed using a standardised 0–1 scale, where:

- 1.0 = optimal DfD performance (e.g. dry, reversible, accessible systems)
- 0.75–0.25 = intermediate performance levels
- 0.0 = poor or irreversible performance (e.g. bonded or inaccessible systems)

Scoring is based on qualitative descriptors and defined criteria (where available), supported by professional judgement at design stage.

Scores are:

- Aggregated from indicator → category → level
- Normalised to produce a total DfD score (0–100)
- Presented in tabular or graphical form for comparison

To improve representativeness, the method incorporates:

- Material volume factors, ensuring proportional influence of elements
- Optional weighting, including:
    - Category weighting (e.g. emphasis on physical aspects: Systems, Technical, Materials)
    - Hierarchy weighting (greater weight to element/component levels reflecting higher reuse value)

The method enables cross-system comparison and benchmarking, but is subject to limitations including time intensity, data availability, and scoring subjectivity, particularly for process and data indicators.

For further details see

Daly, P., & Barril, P. G. (2025). Development and pilot application of a novel design for disassembly assessment framework and method entitled 'STaMPD'—applied in the design and prototyping of a modular circular wall over cladding system. *Journal of Building Design and Environment*. https://doi.org/10.70401/jbde.2025.0021