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Circularity and Carbon Performance of Prefabricated Biobased Modular Systems: A Comparative Analysis of Cases and Life Cycle Assessment Methods

Assessing environmental / circularity benefits of integrating biobased materials within prefabricated panelised – modular framed construction systems, critiquing LCA methods – toward optimising environmental / carbon and circular performance.

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ABSTRACT

The construction sector faces escalating pressure to reduce embodied greenhouse gas emissions while transitioning from linear material use toward circular, regenerative systems. Biobased modular wall assemblies designed for disassembly and reuse are increasingly promoted as a pathway to address both challenges; however, robust empirical comparisons with conventional construction remain limited, particularly when assessed across different life cycle assessment (LCA) methods and circularity assumptions.

This paper presents a comparative, multi tool, and multi cycle LCA of prefabricated biobased modular wall systems developed within two EU research and demonstration projects (Drive 0 and Circ Reno), benchmarked against conventional external wall insulation systems in retrofit contexts and masonry cavity wall construction in new build scenarios. Environmental performance was assessed using ICE database screening, Ubakus elemental LCA, and OneClick LCA whole building modelling, applying harmonised functional units but varying system boundaries and datasets in order to explicitly examine methodological sensitivity. Both single life (100:0) and multi cycle allocation scenarios (Linear Degressive and Circular Economy Linear Degressive) were explored to evaluate how design for disassembly and reuse potential are represented within current LCA frameworks.

Results show that, under single life cycle assessment, modular systems may exhibit higher mass and embodied impacts than lightweight bonded solutions, particularly where additional framing, fixings, and protective layers are required. However, increasing levels of biobased material integration substantially reduces embodied carbon intensity, and results are highly sensitive to database choice, system boundaries, and biogenic carbon accounting conventions. When multi cycle reuse scenarios are applied, modular systems designed for disassembly demonstrate 21–45% reductions in cumulative embodied GWP relative to conventional systems, depending on the allocation method adopted. In a high biobased new build prototype incorporating straw based insulation and timber construction, embodied carbon was reduced by 72% per m² compared with an equivalent performance masonry cavity wall, while meeting passive level thermal targets.

The study demonstrates that circular and biobased construction outcomes cannot be meaningfully interpreted through single life, linear LCAs alone. At the same time, it highlights significant uncertainties related to dataset maturity, proxy environmental product declarations, future reuse assumptions, and allocation choices. Rather than presenting definitive performance rankings, the paper positions these results as conditional insights, illustrating how methodological decisions shape the visibility—and potential undervaluation—of circular design strategies within current LCA practice. The findings underscore the need for improved data availability for biobased materials, transparent alignment of allocation methods with decision making contexts, and policy frameworks capable of recognising multi cycle building systems as temporary material infrastructures rather than disposable products.

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1. Introduction

1.1. Background and Context

The construction sector sits at the centre of global sustainability challenges due to its extensive resource consumption, high levels of waste generation, and significant contributions to greenhouse gas (GHG) emissions. When upstream industrial processes such as cement and steel manufacture are included, the built environment is responsible for 37% of global energy- and process-related emissions [1] . In the European Union (EU), the existing building stock accounts for 40% of final energy use and 36% of energy-related emissions, underscoring its centrality to the EU's renovation trajectory [2]. Similar patterns exist nationally: in Ireland, the built environment contributes 37% of total GHG emissions, with residential buildings representing more than 60% of this share [3] .

This accumulation of emissions is not merely an operational energy issue; rather, it increasingly reflects the growing significance of embodied energy and carbon, the energy and emissions associated with material extraction, manufacturing, construction, maintenance, and end-of-life processes. As operational energy demand declines through efficiency improvements and progressive decarbonisation of electricity grids, relative embodied emissions are projected to dominate whole-life impacts in many building typologies [4, 5]. Indeed, in highly efficient buildings, embodied emissions can represent 45–50% of total life cycle carbon, and significantly more in regions with low-carbon energy systems [4]. Moreover, upstream manufacturing stages (A1–A3) typically contribute the majority, often more than 70%, of embodied energy / carbon in European contexts [3, 4]. These trends have profound implications for building and retrofit policy and practice, as efforts to reduce operational energy without addressing embodied carbon may yield limited net environmental benefit or even cause "carbon rebound" effects [6].

1.2. The Potential and Challenge of Circularity and Biobased Construction

In response to these challenges, the circular economy (CE) has emerged as a prominent framework for reconfiguring construction towards regenerative, low-carbon practices. The CE paradigm, widely defined as "restorative and regenerative by design" [7], promotes strategies that retain materials and components in productive use for longer, reduce waste, and enable high-value recovery. Within the built environment, CE strategies include design for disassembly (DfD), component reuse, modularisation, and the substitution of carbon-intensive materials with renewable biobased alternatives [6, 8]. Modelling studies suggest that circularity oriented strategies could reduce global emissions from construction materials by up to 38% by 2050 [9].

Biobased materials play a distinctive role within this transition. Derived from renewable biological sources, such as timber, hemp, straw, cellulose and bio-composites, biobased materials offer several advantages:

1. Biogenic carbon storage: atmospheric carbon absorbed during growth remains stored within materials throughout their service life [10].
2. Low embodied energy: many biobased materials require significantly less process energy than mineral or petrochemical alternatives [11].
3. Compatibility with circular flows: biobased materials can often be mechanically disassembled, reused, recycled, or returned safely to biological cycles [12].
4. Regionalised supply chains: agricultural residues and short-rotation crops facilitate localised production with reduced transport emissions [13].

However, the environmental benefit of biobased materials is highly contingent on service life, reuse pathways, and end-of-life scenarios, which remain uncertain and context-dependent, despite an expanding research base, especially in multi-cycle contexts. Biogenic carbon accounting varies substantially across standards, datasets, and tools [14, 15] and many biobased materials lack EN15804 compliant datasets, limiting the robustness of life cycle assessments [3].

1.3. Modular Construction and Design for Disassembly as Enablers of Circularity

Alongside biobased material innovation, modular and prefabricated construction has gained renewed attention as a structural enabler of circularity. Off-site manufacturing enhances quality control, reduces material waste, and can facilitate standardisation and repeatability of components [16]. When aligned with DfD principles, including reversible mechanical fixings, layered assemblies, and accessible interfaces, modular systems can support high levels of component reuse and multi-life construction pathways [17, 18]. Empirical studies indicate that modularisation can reduce construction waste by up to 70% and improve material recovery rates compared to conventional construction [19].

Yet modular and DfD-enabled systems often introduce additional layers, sub-frames, and fixings, which can increase upfront material mass and embodied impacts when assessed under conventional single-cycle LCA. Empirical studies consistently show that such systems may appear environmentally disadvantageous when future reuse is not accounted for [18]. This tension between higher upfront impacts and longer-term circular potential is central to evaluating modular biobased systems and remains insufficiently addressed within standard LCA practice.

Empirical evidence evaluating modular retrofit panels, particularly those integrating high proportions of biobased materials, remains sparse. Several prototypes developed through EU research initiatives (e.g., Drive 0, Circ Reno) offer promising models and provide a test case for environmental – circular performance assessment [20, 21].

1.4. Retrofit as a Strategic Opportunity and Test Case

Deep retrofit represents one of the most impactful opportunities for decarbonising the built environment. With the vast majority of 2050's building stock already constructed, more than 85% of existing EU buildings are expected to remain in use, and around 75% are energy-inefficient, renovation is essential not only for emission reduction but also for improving resilience and alleviating energy poverty [22, 23]. The EPBD [24] places increasing emphasis on embodied carbon, life cycle performance, and circularity within renovation strategies [2].

Within the retrofit domain, External Wall Insulation (EWI) remains a widely adopted measure for improving envelope performance. However, mineral and petrochemical-based EWI systems (e.g., EPS, PIR, XPS) often involve high embodied carbon, limited recyclability, and irreversible installation methods, challenging their alignment with long-term circularity objectives [25, 26]. As retrofit programmes scale, the cumulative embodied emissions associated with conventional EWI may risk undermining national and EU climate targets [26, 27].

As retrofit programmes scale, the cumulative embodied emissions associated with such single-use façade systems become increasingly significant. Modular biobased over-cladding panels designed for mechanical installation and removal have therefore been proposed as an alternative approach that could combine operational energy savings with improved circularity. Nevertheless, empirical LCA evidence comparing such systems with conventional practice remains limited, and published results are often highly sensitive to modelling choices and system boundaries.

1.5. Life Cycle Assessment Challenges for Circular Systems

Life Cycle Assessment (LCA) has become the dominant method for evaluating environmental impacts of building materials and systems and is reported as the principle tools for assessing circularity, despite acknowledgement of limitations notably in relation to DfD and multi-cycle systems [28, 29]. Key challenges include:

1. Linear assumptions in standard LCA frameworks, which do not reflect multi-use, multi-life pathways [18].
2. Inconsistent system boundaries across studies [30].
3. Variability in datasets and modelling choices, affecting comparability [31].

4. Uncertainty in biogenic carbon modelling under EN15804+A2 [32].
5. Lack of consensus on allocation methods for multi-cycle modelling [33, 34].

As a consequence, identical physical systems may appear to perform significantly better or worse depending on the assessment tool, database, and allocation approach applied, complicating interpretation for designers and policymakers alike.

1.6. Research Aim and Questions

This study addresses these challenges through a comparative, multi-tool, and multi-cycle LCA of biobased modular wall systems developed within two EU research and demonstration projects [20, 21]. Rather than establishing definitive performance rankings, the paper is primarily positioned as a methodological–empirical investigation into how different LCA approaches and allocation choices shape the representation of circular, biobased construction systems and secondarily as a comparison of biobased panelised systems compared to conventional, with panels differing in biobased material content, structural approach, and design-for-disassembly criteria, enabling analysis across a spectrum of circularity potentials.

1.6.1. Primary Research Question

What is the whole-life carbon - circularity performance of biobased integrated modular wall systems - applied in building retrofit and new build contexts, and how do different LCA methodological approaches affect this assessment?

1.6.2. Sub-questions

How does the comparative representation of biobased modular retrofit systems versus conventional EWI vary under different LCA boundaries, datasets, and tools?

How do different multi-cycle allocation methods (100:0, LD, CELD) influence the quantification of reuse and circularity benefits?

How does Design for Disassembly influence the representation of upfront and whole-life carbon impacts within single- and multi-cycle LCA frameworks?

Which data limitations and methodological uncertainties most strongly affect the robustness and interpretability of LCA results for biobased modular systems?

While only GWP is discussed in detail here, other impact categories (e.g., land use, toxicity) are acknowledged as relevant but lie beyond the scope of this policy-aligned embodied carbon analysis

1.7. Contribution

This paper makes three distinct and complementary contributions to the literature on circular construction and environmental assessment.

First, it provides new empirical life cycle assessment evidence for prefabricated biobased modular wall systems developed within two EU research and demonstration projects [20, 21]. The study reports comparative results for retrofit and new-build façade systems designed to achieve functionally equivalent thermal performance, addressing a well-documented lack of empirical data for modular biobased construction in European contexts.

Second, the paper offers a methodological contribution by explicitly examining how different LCA tools, datasets, system boundaries, and allocation approaches influence the representation of circularity and embodied carbon outcomes. By applying multiple LCA tools (ICE, Ubakus, OneClick LCA) and contrasting single-life and multi-cycle allocation methods (100:0, Linear Degressive, Circular Economy Linear Degressive), the study demonstrates that quantified environmental performance is highly sensitive to methodological choice, particularly for systems designed for reuse and disassembly.

Third, the paper contributes conceptual insight by reframing modular biobased façade systems as temporary material infrastructures rather than single-use construction products. In doing so, it highlights structural limitations of conventional linear LCA frameworks when applied to circular construction and underscores the importance of aligning assessment methods with decision-making contexts in design, procurement, and policy.

Importantly, the paper does not seek to establish definitive performance rankings or predict realised future reuse outcomes. Instead, results are presented as conditional and scenario-dependent, illustrating how circular design strategies may be undervalued or revealed depending on assessment assumptions.

2. Research Methods

2.1. Research Design and Analytical Framework

This research employs a comparative, case-based life-cycle assessment (LCA) design to evaluate how different LCA tools, system boundaries, and allocation methods represent the embodied carbon and circularity performance of biobased modular wall systems relative to conventional construction. Rather than seeking to establish definitive rankings of construction systems, the study is primarily structured as a methodological–empirical investigation, using real prototype assemblies to explore the sensitivity of environmental outcomes to modelling choices and secondarily to examine system performance impacts.

The analytical framework integrates:

- multiple physical façade system case studies,
- multiple LCA tools and databases,
- multiple life-cycle modelling approaches (single-life and multi-cycle),
- and functionally equivalent performance criteria (thermal transmittance).

This triangulated approach allows the study to examine not only *what results are obtained*, but why results differ under alternative methodological assumptions. Such an approach responds to well-documented challenges in circular construction LCA, including database variability, linear system assumptions, and the treatment of reuse and biogenic carbon [31, 35].

This triangulation is used to examine how assessment methodologies influence results, an important theme in circularity research given well-documented inconsistencies in LCA practice

The overarching methodological aim is therefore twofold:

1. To evaluate how methodological choices—especially allocation rules and tool selection—affect the representation of circularity benefits.
2. To critique the whole-life environmental performance of biobased modular retrofit systems.

This design aligns with recognised LCA guidance (ISO 14040/44; EN 15804+A2; EN 15978) while extending standard practice through the application of multi-cycle modelling to systems designed for reuse.

2.2. Case Selection and Experimental Logic

The study draws on façade system prototypes developed within two EU research and demonstration programmes: Drive 0 and Circ Reno. These projects were selected because they provide:

- physically realised modular panel designs,
- varying levels of biobased material integration (low, medium, high),
- explicit design-for-disassembly (DfD) strategies,
- and prior environmental assessments suitable for comparative re-analysis.

Four LCA studies were analysed, each addressing a specific methodological question rather than forming an arbitrary sequence:

- **Study 1** explores early-stage material intensity and screening-level embodied impacts.
- **Study 2** tests the influence of tool and database choice using identical assemblies.
- **Study 3** examines the effect of single-life versus multi-cycle allocation approaches.
- **Study 4** extends the analysis to a highly bio-intensive new-build prototype.

Collectively, these studies form a designed methodological experiment that isolates the influence of material composition, modelling boundaries, and circularity assumptions on LCA outcomes. Fig. (**1**) showing schematic of projects, prototype modular systems v conventional lightweight retrofit and heavy weight masonry and the four LCA assessment studies. See Table **1** presenting a summary of the four Studies / LCA Assessments, tools, database and boundaries.

See Appendix **A** for detailed summary of construction systems.

Table 1: Study / LCA summary.

Phase	Study	Panel Systems	Tool / Data	System Boundary	Purpose
1	Study 1 – ICE Screening	Drive 0 Low Bio vs EPS EWI U 0.18	ICE Database	A1–A3 (Cradle-to-Gate)	Early-stage screening and material intensity exploration, enabling rapid benchmarking of low-biobased façade concepts against conventional EPS systems.
2	Study 2a – Elemental LCA	Drive 0 Low Bio vs EPS EWI U 0.18	Ubakus	A1–A3 (Cradle-to-Gate)	Façade system comparison using elemental LCA to refine material quantities and environmental performance.
	Study 2b – Whole Building LCA	Drive 0 Low Bio vs EPS EWI U 0.18	OneClick	A1–A5, B4–B6, C1–C4 (Cradle-to-Grave)	Building-level impact assessment including construction, operational replacement, and end-of-life stages. Enables cross-tool/data comparison.
3	Study 3a – Refined WBLCA	Drive 0 Mid Bio vs EPS EWI U 0.18	OneClick LCA	A1–A5, B4–B6, C1–C4 + D (Cradle-to-Grave + benefits beyond boundary)	Refined building LCA with updated datasets and increased biobased content, assessing potential benefits beyond system boundary.
	Study 3b – Multi-Cycle LCA	Drive 0 Mid Bio vs EPS EWI U 0.18	OneClick LCA	A1–A5, B4–B6, C1–C4 + D	Circularity modelling using multiple allocation scenarios: Baseline OCLCA, MLC, MLC 100:0, and LMC-LD, exploring reuse and multi-life cycle impacts.
4	Study 4 – High Bio Prototype Passive	Circ Reno High Bio Panels (300 mm) U 0.14	OneClick LCA	A1–C4 (Cradle-to-Grave)	Environmental assessment of high biobased façade panel prototypes, evaluating material innovation and performance.

Note: Where Module B6 is included (Studies 2b, 3a, 3b), operational energy use is assumed to be equivalent across all cases due to identical thermal performance (U-values). B6 does not affect comparative results and is not reported separately.

2.3. Functional Unit and Performance Equivalence

To enable meaningful comparison, the functional unit (FU) is defined as:

1 m² of external wall assembly achieving equivalent thermal performance, assessed over a 60-year reference study period (RSP).

Target thermal transmittance values are:

- 0.18 W/m²K for retrofit assemblies,
- 0.14 W/m²K for new-build assemblies.

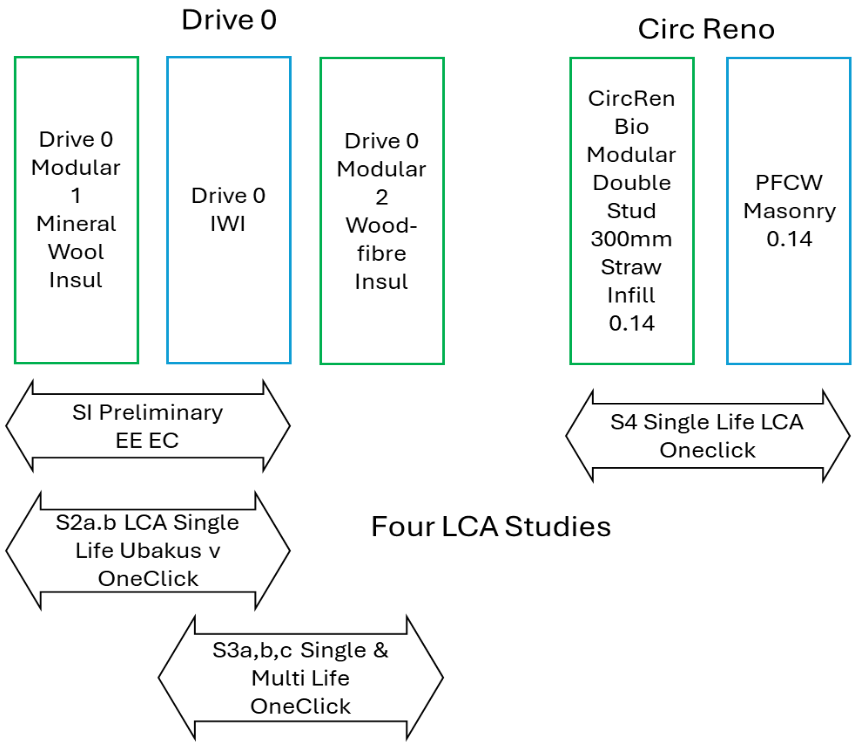

Figure 1: Showing schematic of projects, case studies and LCA studies / sequence.

Operational energy use is excluded from the system boundary on the basis of functional equivalence, ensuring that differences in results reflect material systems and construction strategies, rather than variations in operational performance.

2.4. System Boundaries and Life-Cycle Stages

The primary system boundary adopted is cradle-to-grave (A1–C4) in accordance with EN 15804 +A2 and EN 15978, with selective inclusion of Module D in multi-cycle scenarios.

Included stages:

- **A1–A3**: raw material extraction, transport, and manufacturing
- **A4–A5**: transport to site and construction
- **B4**: component replacement (where applicable)
- **C1–C4**: deconstruction, transport, processing, and disposal
- **Module D**: benefits and loads beyond the system boundary (where applicable)

Operational energy use (Module B6) is not a decision-determining variable in this study. All façade systems analysed are designed to achieve functionally equivalent thermal performance (U-values of 0.18 W/m²K for retrofit and 0.14 W/m²K for new-build).

As a result, operational energy demand is assumed to be equivalent across all compared systems. In several studies (Studies 1, 2a, 3b), B6 is therefore excluded from the system boundary. In one whole-building case (Study 2b), B6 is included by default within the OneClick LCA model; however, it does not influence comparative outcomes and is not interpreted as a differentiating factor.

The study therefore focuses on embodied impacts and circularity representation, and excludes use-phase energy as a source of comparative bias.

2.5. LCA Tools, Databases, and Data Sources

To explicitly test database and software sensitivity, three established LCA tools were applied:

- **ICE database (v3.0)** for early-stage embodied energy and carbon screening,
- **Ubakus** for elemental LCA using Ökobau.dat-based generic EPD datasets,
- **OneClick LCA** for whole-building and element-level assessment using EN 15804-compliant EPD libraries.

Material data were prioritised according to EN 15804 hierarchy:

1. Product-specific verified EPDs,
2. Industry-average EPDs,
3. Generic database proxies where product-specific data were unavailable.

For emerging or agricultural biobased materials lacking product-specific data (e.g. straw-based infill), proxy datasets with comparable density and function were adopted. The use of proxy data is treated as a structural limitation of current data availability, and results are interpreted accordingly.

2.6. Multi-Cycle Modelling and Allocation Approaches

To represent systems designed for reuse and disassembly, both single-life and multi-cycle assessment approaches were applied.

Single-life modelling uses a 100:0 allocation, assigning all production impacts to the first life cycle.

Multi-cycle modelling explores reuse across up to three service lives, applying three established allocation approaches:

- 100:0 (conservative, near-term policy alignment),
- Linear Degressive (LD) allocation,
- Circular Economy Linear Degressive (CELD) allocation.

These allocation methods are not treated as competing truths, but as representations aligned with different decision-making contexts (e.g. regulatory compliance, circular procurement, design optimisation). Module D benefits are applied cautiously to avoid double counting and are interpreted in conjunction with multi-cycle results rather than as additive credits.

2.7. Treatment of Biogenic Carbon and End-of-Life Scenarios

Biogenic carbon is modelled in accordance with EN 15804 +A2 conventions, whereby carbon uptake during biomass growth is accounted for in A1 and release is assumed to occur at end of life depending on disposal pathways. Default end-of-life scenarios reflect European averages for recycling, incineration with energy recovery, and landfill.

Negative production-stage GWP values are therefore reported as temporary storage effects, not net climate neutrality. The representation of biogenic carbon is explicitly acknowledged as method-dependent, and its influence on comparative results is discussed qualitatively alongside quantitative findings.

2.8. Limitations and Interpretation Strategy

The methodological design intentionally emphasises transparency over optimisation. Results are interpreted as conditional outcomes under specified assumptions, rather than predictions of realised future performance. Key limitations include:

- dataset immaturity for biobased materials,
- reliance on proxy EPDs,
- uncertainty in future reuse rates,
- exclusion of dynamic temporal modelling.

By presenting multiple modelling perspectives on the same physical systems, the study aims to clarify how methodological decisions shape LCA outcomes for circular construction, rather than to eliminate uncertainty entirely.

3. Literature Review

3.1. Circularity and Decarbonisation in the Built Environment

The construction sector is a major contributor to global greenhouse gas (GHG) emissions, driven by both operational energy use and the energy-intensive production of key materials such as cement and steel. As operational emissions decline through improved energy efficiency and electricity grid decarbonisation, embodied emissions increasingly dominate whole-life impacts, shifting attention toward materials, construction systems, and end-of-life strategies [4, 5].

In response, the circular economy (CE) has gained prominence as a systemic framework aimed at reducing resource throughput, extending service life, and retaining material value by prioritising reuse and recovery over disposal [7, 8]. Within the built environment, CE principles are commonly operationalised through modularisation, design for disassembly, component reuse, and selective material substitution. Modelling studies suggest that widespread adoption of circular strategies could reduce emissions from construction materials by approximately 38 % by mid-century [9].

However, despite growing policy and academic attention, CE implementation in construction remains contested. Reviews consistently report heterogeneity of definitions, inconsistent methodological approaches, and weak comparability across studies, particularly where circularity is assessed through life cycle assessment (LCA) using differing system boundaries, databases, and allocation rules [33, 36-38]. These challenges illustrate a dual problem: translating CE principles into buildable systems, and developing assessment methods capable of capturing circular value without reinforcing linear assumptions [39, 40].

3.2. Biobased Materials: Carbon Storage, Performance, and Controversies

Biobased materials (e.g., timber, straw, hemp, cellulose, cork and other lignocellulosic products) are a cornerstone of low-carbon and circular construction agendas because they (i) store biogenic carbon sequestered during growth, (ii) often require lower process energy relative to petrochemical/mineral alternatives, and (iii) can be more readily integrated into reusable or biodegradable end-of-life pathways [6, 10]. Multiple studies find that substituting conventional materials and insulation with biobased alternatives can significantly reduce embodied carbon and, in some contexts, achieve net-negative partial balances over the use phase due to storage effects [11, 41].

At the same time, biogenic carbon accounting is a persistent source of controversy. Under EN 15804+A2, carbon uptake during growth is credited in A1 (as negative GWP bio), while full release is assumed at end-of-life depending on the disposal route, with temporary storage reported only as an informational indicator rather than reducing GWP [42]. This treatment can erase the perceived benefit of storage unless Module D or multi-cycle modelling accounts for reuse, cascaded use, or delayed emissions [15, 43]. Further, results are sensitive to end-of-life assumptions (e.g., incineration with energy recovery vs. reuse vs. biodegradation) and dataset availability/quality, which remain limited for many biobased materials [3, 14].

Beyond carbon, critical appraisals highlight performance pluralities—hygrothermal behaviour, durability, fire safety, and the life-cycle implications of chemical treatments and binders [44, 45]. For instance, poor design detailing that traps moisture can undermine both service life and expected environmental benefits; conversely, diffusion-open assemblies can mitigate risks while enabling disassembly and reuse. These practicalities underscore the importance of system-level evaluation (material + build-up + connections) rather than material substitution in isolation.

3.3. Modularity and Design for Disassembly (DfD)

Modular construction leverages off-site fabrication to improve quality control, reduce waste, and enable standardised, replaceable assemblies [6]. When combined with Design for Disassembly (DfD), reversible mechanical fixings, accessible interfaces, separation of layers, modular systems can significantly increase reuse potential of components and materials [17]. The literature identifies connection typologies (from gravity and mechanical to adhesive/material bonds) as a critical determinant of disassembly feasibility and value retention [17]. Layered design (structure, skin, services, space plan) aids in aligning replacement cycles with the shortest-life elements, a principle central to circularity [46].

However, modularisation and DfD can increase upfront material use (e.g., additional sub-frames, fixings, interfaces) which may raise embodied impacts in single-cycle LCAs [18, 47]. The environmental payoff therefore depends on design and realised reuse rates, quality retention, and number of cycles—factors often treated as assumptions rather than empirically verified. Barriers include market acceptance of reused components, logistics and certification, and dimensional standardisation across projects. Case studies of reusable modules and biobased panels (e.g., straw-based systems) report promising circular profiles but are variably documented in LCA terms, limiting broader generalisation [19 , 48].

3.4. Retrofit and Over-Cladding: Decarbonisation, Lock-in, and Material Choices

Retrofit is central to meeting climate goals because the majority of 2050's building stock already exists, often with poor thermal performance [2]. External Wall Insulation (EWI) is a widely deployed measure with strong operational benefits, yet the literature cautions that high-performance insulation can substantially increase embodied carbon, potentially delaying net emission reductions if whole-life effects are not managed [27, 49]. This risk is amplified when EWI systems rely on bonded petrochemical insulants (e.g., EPS, PIR, XPS) that are difficult to disassemble or recycle and often end in landfill or energy recovery [50].

Systematic reviews of refurbishment LCAs emphasise context sensitivity (climate, grid carbon factors, building typology) and the need to avoid carbon lock-in by prioritising measures with short payback and high reuse potential [6, 51]. Against this backdrop, biobased modular over-cladding emerges as a promising pathway, potentially combining operational gains with lower embodied GHG and higher circularity, provided that durability, moisture risk, and maintenance are addressed through robust design and testing [52, 53].

3.5. Life Cycle Assessment for Circular Systems: Standards, Biogenic Carbon, Allocation, and Data

Standards and scope: LCA provides a transparent framework for environmental assessment [54], with EN 15804+A2 (product) and EN 15978 (building) specifying life-stage modules and reporting (A1–C4; optional D). However, standard LCA remains fundamentally linear, and as such does not inherently represent multi-life circular flows [38, 39].

Biogenic carbon: As noted, EN 15804+A2 treats sequestration and release in a way that often yields no net GWP benefit across a single life, unless Module D (beyond boundary benefits) or multi-cycle reuse is modelled; time-dependent effects are typically excluded [42, 43]. This further motivates multi-cycle approaches for biobased systems [14, 15].

Allocation across multiple cycles: Several allocation schemes exist to distribute impacts and benefits across sequential lifecycles: 100:0, 50:50, Circular Footprint Formula, Linear Degressive (LD), CELD, SIA 2032 (variants), and structural degradation models [33, 34, 39, 40]. Evidence suggests that results are highly sensitive to the chosen allocation, with 100:0 offering conservative, policy-aligned snapshots but undervaluing reuse benefits; LD and especially CELD more closely reflect circular value retention but introduce assumptions about quality decay and future reuse that are uncertain [34, 40]. When Module D is used, care is required to avoid double counting benefits already implied by multi-cycle allocation [55].

Data and software variability: Comparative studies repeatedly show that different LCA tools and databases (e.g., One Click LCA vs. German Ökobau.dat via Ubakus) yield non-trivial differences due to varying background datasets, assumptions, and EPD coverage [31, 49]. For biobased materials, dataset availability and compliance with EN 15804+A2 remain uneven, increasing uncertainty and limiting benchmarking [3]. These challenges strengthen the case for multi-tool triangulation and explicit uncertainty/sensitivity analysis [56].

Design for Disassembly in LCA: A specific concern is that DfD systems may appear worse in single-cycle LCAs due to added fixings and sub-structures, with benefits realised only in later cycles or Module D [34, 47]. Reviews consistently recommend multiple life cycles or explicit reuse crediting to avoid penalising designs with longer-term circular value [33, 38].

Dynamic LCA (DLCA): Dynamic modelling that accounts for temporal aspects (e.g., timing of emissions and storage, grid decarbonisation) can better reflect real-world performance but remains data-intensive and under-standardised for buildings, limiting adoption [18, 57].

3.6. Synthesis and Study Positioning

The literature converges on several points germane to this study:

1. Circularity requires system-level strategies, not merely material substitution: modularity, reversible connections, and layered design are central enablers [16, 17].
2. Biobased materials can reduce embodied carbon and store biogenic carbon, but single-life LCAs may understate benefits due to EN 15804+A2 accounting and end-of-life assumptions [10, 42].
3. Conventional bonded EWI delivers operational benefits, but risks embodied carbon lock-in, limited reuse potential, and downcycling at end-of-life [26, 50].
4. Methodological inconsistencies, system boundaries, datasets, allocation rules, undermine comparability; multi-tool triangulation and transparent assumptions are needed [31].
5. Allocation choice matters: 100:0 aligns with near-term policy metrics, whereas LD/CELD better reflect circular design intent; neither is universally “correct” outside a clear decision context [34, 40].

These insights motivate the present study’s comparative, multi-tool, and multi-cycle approach, using real modular façade systems to examine how methodological choices shape the representation of circularity and embodied carbon performance.

4. Results

4.1. Overview of Reported Results

This section presents the results of the comparative Life Cycle Assessment (LCA) studies defined in Section 2. Results are reported by assessment study, following the methodological sequencing outlined in the methods. Each set of results is therefore tied to a specific combination of physical system, tool, database, system boundary, and allocation approach.

The purpose of this section is primarily to report quantified environmental outcomes under stated modelling assumptions, not to evaluate their desirability or policy implications. Interpretation of the results is developed in Section 5. Unless otherwise noted, results relate to embodied environmental impacts, with Global Warming Potential (GWP, $kgCO_2e$) used as the primary indicator. Operational energy use (Module B6) is excluded or treated as functionally equivalent across all cases and does not influence comparative outcomes.

4.2. Study 1 – Screening-Level Assessment (ICE Database, A1–A3)

Study 1 presents a screening-level comparison of the Drive 0 low-biobased modular retrofit system and a conventional EPS-based external wall insulation (EWI) system. The analysis is limited to cradle-to-gate stages (A1–

A3) and uses the ICE v3.0 database to provide an early-stage indication of material intensity, embodied energy, and embodied carbon.

The modular system has a substantially higher total material mass than the EWI system, at 3948 kg compared with 2145 kg, representing an increase of approximately 84%. This reflects the additional framing, fixings, and layered build-up associated with prefabrication and design-for-disassembly strategies. Correspondingly, embodied energy over A1–A3 is significantly higher for the modular system at 37,847 MJ, compared to 15,579 MJ for the EWI system, an increase of approximately 143%, largely attributable to light gauge steel and cement-based façade components.

Embodied carbon results over the same boundary show a smaller relative difference. The modular system records 669 $kgCO_2e$, compared to 585 $kgCO_2e$ for the EWI system, representing an increase of approximately 14.4%. These results highlight the material and energy intensity effects of modular construction under simplified, single-life and cradle-to-gate assumptions, and serve as a baseline reference for more detailed assessments.

Fig. (**2**) showing results comparison from this study for mass, EE and EC [58].

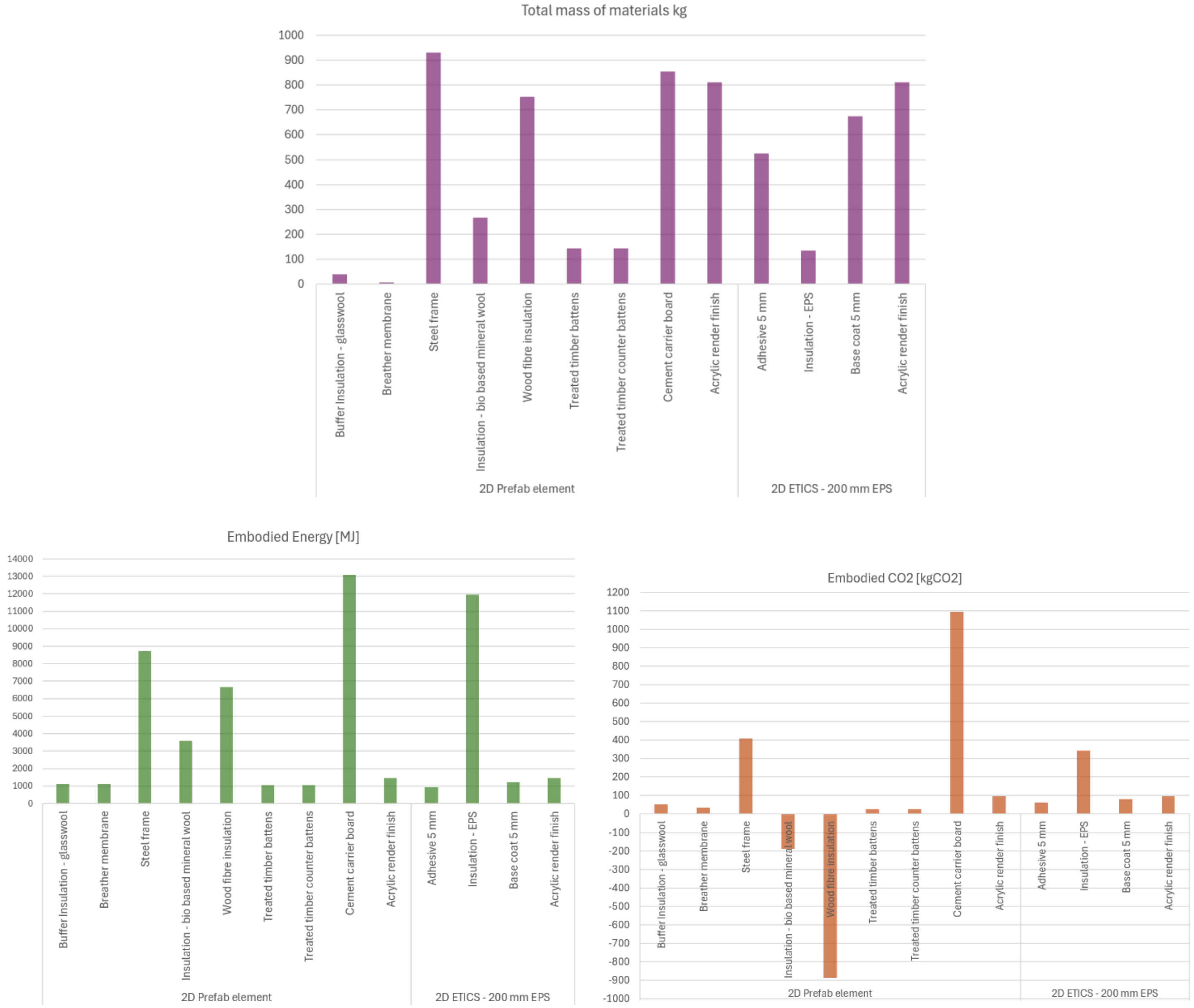

Figure 2: Showing (Upper) Mass, (Lower-Left)- EE and (Lower-Right)- EC for the Modular – 2D prefabricated modular compared to conventional EWI systems. [58] Source (Daly, 2025).

4.3. Study 2 – Sensitivity to LCA Tool and Database Choice

4.3.1. Study 2a: Element-Level LCA (Ubakus, A1–A3)

Study 2a evaluates the same physical retrofit systems as Study 1 using the Ubakus elemental LCA tool, drawing primarily on generic Ökobau.dat datasets and limiting the boundary to A1–A3. Results are reported per square metre of wall assembly.

The modular system again exhibits greater material mass, at 38.5 kg/m², compared to 26.3 kg/m² for the conventional EWI system (+46.4%). Non-renewable primary energy demand is also higher for the modular system, at 78 kWh/m², compared with 68 kWh/m² for EWI (+14.7%).

However, embodied carbon results differ markedly from Study 1. Under the Ubakus datasets, the modular system achieves a GWP of 8.4 $kgCO_2e/m^2$, compared to 13.0 $kgCO_2e/m^2$ for the EWI system. This corresponds to an approximate 35.4% reduction in embodied carbon for the modular system under A1–A3 conditions. The divergence from Study 1 reflects differences in database composition, material carbon intensity values, and treatment of biobased components within the Ubakus framework.

4.3.2. Study 2b: Whole-Building LCA (OneClick LCA, A1–C4)

Study 2b re-assesses the same low-biobased modular and conventional EWI systems using OneClick LCA at whole-building level, with wall-element results extracted. The system boundary is expanded to cradle-to-grave (A1–C4), incorporating construction, replacement, and end-of-life stages.

Under these conditions, the modular wall system records a total embodied carbon of 6987 $kgCO_2e$, compared with 3845 $kgCO_2e$ for the EWI system. This represents an increase of approximately 81.7% for the modular solution. The change in relative performance compared to Studies 1 and 2a is attributable to the inclusion of additional life-cycle stages and to default assumptions regarding end-of-life processing and biogenic carbon release within the OneClick LCA database.

Taken together, Studies 2a and 2b demonstrate that comparative embodied carbon outcomes for identical physical systems are highly sensitive to tool selection, database structure, and life-cycle boundary definition.

4.4. Study 3 – Single-Life and Multi-Cycle Modelling (OneClick LCA)

Study 3 evaluates a mid-biobased variant of the Drive 0 modular retrofit system relative to conventional EWI using OneClick LCA. Compared to Study 2, the modular system incorporates a higher proportion of biobased materials, primarily through substitution of mineral insulation with wood-fibre insulation.

4.4.1. Study 3a: Single-Life-Cycle Assessment (A1–C4)

Under single-life cradle-to-grave modelling, total building-level embodied carbon for the modular system is 15,241 $kgCO_2e$, compared with 16,362 $kgCO_2e$ for the EWI system, representing a reduction of approximately 6.9% at building scale.

At the extracted wall-element level, however, the modular system records 6384 $kgCO_2e$, compared to 5317 $kgCO_2e$ for the EWI system, corresponding to an increase of approximately 20.1%. This reflects the continued influence of additional framing, interfaces, and fixings at element level despite increased biobased content.

4.4.2. Study 3b: Multi-Cycle Assessment (A1–C4 + D)

Study 3b extends the analysis by applying multi-cycle modelling over up to three service lives using different allocation approaches. The physical construction system remains unchanged; only allocation assumptions differ.

Under the baseline multi-cycle scenario, cumulative wall-level embodied carbon for the modular system over three life cycles are 15,375 $kgCO_2e$, compared to 19,539 $kgCO_2e$ for the EWI system, representing a reduction of approximately 21.3%. When 100:0 and Linear Degressive allocation methods are applied, cumulative embodied carbon for the modular system reduces further to 10,737 kgCO₂e, corresponding to reductions of approximately 45.0–45.1% relative to the EWI system.

These results demonstrate that multi-cycle allocation assumptions strongly influence cumulative embodied carbon outcomes, particularly for systems designed for disassembly and reuse.

4.5. Study 4 – High-Biobased Modular System in New-Build Context (Circ Reno, A1–C4)

Study 4 assesses a high-biobased modular wall system developed within the Circ Reno project for new-build applications, compared with a conventional heavy masonry cavity wall system. Both wall types are designed to achieve equivalent high-performance thermal standards (U-value ≈ 0.14 W/m²K).

At wall-element level over the A1–C4 boundary, the conventional masonry wall records 81.6 kgCO₂e/m², while the biobased modular system records 22.7 kgCO₂e/m², representing an embodied carbon reduction of approximately 72%.

At the production stage (A1–A3), the modular wall exhibits a negative GWP of approximately –90.5 kgCO₂e/m² associated with biogenic carbon uptake, while end-of-life stages (B–C) contribute approximately +112.5 kgCO₂e/m² under default disposal assumptions. These values are reported in accordance with EN 15804 +A2 conventions and reflect temporary biogenic carbon storage rather than permanent sequestration.

See Table **2** for a synthesis of results across all studies, comparing modular to conventional.

Table 2: Results synthesis.

Study	Scope / Metric	Modular System Result	Conventional Comparator	Difference (Modular – Comparator)	% Difference
Study 1 EE EC ICE Cradle to Gate A1-A3 (Low bio)	Mass (kg)	3948	EWI 2145	+1803	+84.0%
	Embodied Energy (MJ)	37847	EWI 15579	+22268	+142.9%
	Embodied Carbon (kgCO₂)	669	EWI 585	+84	+14.4%
Study 2a Elemental LCA Ubakus Cradle to Gate A1-A3 (low bio)	Mass (kg/m²)	38.5	EWI 26.3	+12.2	+46.4%
	EE NRPE (kWh/m²)	78	EWI 68	+10	+14.7%
	EC GWP (kgCO₂e/m²)	8.4	EWI 13	-4.6	-35.4%
Study 2b WBLCA OCLCA Cradle to Grave A1-A5, B4-B6, C1-C4 (low bio)	Whole Wall EC GWP (kgCO₂e)	6987	EWI 3845	+3142	+81.7%
Study 3a WBLCA OCLCA Cradle to Grave A1-A5, B4-B6, C1-C4 (D) (Mid bio)	Total Building EC GWP (kgCO₂e)	15241	EWI 16362	-1121	-6.9%
	Wall EC Scaled Total (kgCO₂e)	6384	EWI 5317	+1067	+20.1%
Study 3b - MLC Baseline OCLCA Cradle to Grave A1-A5, B4-B6, C1-C4 (D) (Mid bio)	Multi-cycle Wall 3 years EC GWP (kgCO₂e)	15375	EWI 19539	-4164	-21.3%
Study 3b - MLC 100:0 OCLCA Cradle to Grave A1-A5, B4-B6, C1-C4 (D) (Mid bio)	Multi-cycle Wall 3 years EC GWP (kgCO₂e)	10737	EWI 19539	-8802	-45.0%
Study 3b - LMC LD OCLCA Cradle to Grave A1-A5, B4-B6, C1-C4 (D) (Mid bio)	Multi-cycle Wall 3 years EC GWP (kgCO₂e)	10737	EWI 19540	-8803	-45.1%
Study 4 OCLCA Cradle to Grave A1-C4 (High bio)	Wall Modular High Bio 300mm Uv 0.14 EC (kgCO₂e/m²)	22.67	PFCW 81.58	-58.91	-72%

Note: Results presented relate to embodied impacts only. Operational energy (Module B6) is excluded or functionally equivalent across cases and therefore not reported.

4.6. Cross-Study Synthesis of Environmental and Circular Performance

Across all studies, the results indicate that:

- embodied carbon outcomes are strongly conditioned by application context (retrofit versus new build);
- biobased material intensity plays a larger role in new-build performance than in incremental retrofit systems constrained by existing structures;
- multi-cycle modelling significantly affects comparative outcomes for modular systems designed for disassembly and reuse; and
- no single embodied carbon result is invariant across tools, databases, or allocation approaches.

These patterns demonstrate that the environmental and circular performance of modular façade systems emerges from the interaction of physical system design and assessment methodology, a relationship explored further in Section 5.

Across the full set of assessment studies, the results show case specific differences in embodied carbon performance between retrofit and new-build applications, as well as strong sensitivity to modelling assumptions.

In retrofit context (Studies 1–3), the specific modular over-cladding systems consistently exhibit higher material mass than conventional lightweight external wall insulation (EWI) systems. Under single-life modelling and extended cradle-to-grave boundaries (A1–C4), this increased material intensity results in higher or comparable embodied carbon at wall-element level, with reported increases up to 20.1% in Study 3a and 81.7% under whole-building modelling in Study 2b. Screening-level and elemental assessments limited to A1–A3 show more variable outcomes, including instances where the modular system records lower embodied carbon than EWI despite higher mass, depending on database and material datasets applied. When multi-cycle allocation approaches are applied to the same retrofit systems (Study 3b), cumulative embodied carbon outcomes change substantially. Across three service lives, the modular retrofit system records lower cumulative embodied carbon than the conventional EWI system in all multi-cycle scenarios, with reductions ranging from approximately 21% to 45%, depending on the allocation method used. These differences arise solely from allocation assumptions, as the physical systems remain unchanged.

In contrast, the new-build application case assessed in Study 4 exhibits a materially different pattern. The high-biobased modular wall system developed within the Circ Reno project demonstrates substantially lower embodied carbon per square metre than the equivalent-performance masonry cavity wall over the A1–C4 boundary, with a reported reduction of approximately 72%. This result is associated with extensive substitution of mineral and petrochemical materials with timber-based and straw-based components and occurs under single-life modelling without the need to assume reuse across multiple service lives.

5. Critical Discussion

5.1. Interpreting Embodied Carbon Outcomes Across Methods and Boundaries

The results presented in Section 4 demonstrate that the environmental performance of biobased modular façade systems cannot be understood independently of the life-cycle assessment (LCA) method applied. Across the four assessment studies, identical or closely related physical systems yield markedly different embodied carbon outcomes depending on database selection, system boundaries, and allocation assumptions. This confirms observations in the literature that methodological decisions are often as influential as material composition in shaping LCA results for construction systems [31, 49].

Screening-level and elemental assessments (Studies 1 and 2a) foreground differences in material mass and production impacts, whereby modular systems exhibit higher mass and energy demand but, under some datasets, lower embodied carbon intensity. In contrast, whole-building cradle-to-grave assessments (Studies 2b and 3a) incorporate construction, replacement, and end-of-life stages, revealing the cumulative impact of additional interfaces, structural components, and default end-of-life assumptions, particularly for biobased materials. These differences illustrate how apparent contradictions between studies reflect modelling scope rather than physical inconsistency.

The findings reinforce the need for caution when comparing LCAs that differ in scope or intent. Results generated under A1–A3 boundaries provide insight into material efficiency and manufacturing impacts but undervalue end-of-life and reuse potential. Conversely, cradle-to-grave assessments may penalise systems designed for disassembly if reuse is not explicitly represented. The study therefore supports calls for transparent boundary definition and decision-context alignment in embodied carbon assessment.

5.2. Mass, Material Intensity, and Carbon Performance

Across all studies, modular façades consistently exhibit higher material mass than conventional lightweight bonded external wall insulation systems. This increase reflects the structural requirements of prefabrication, ventilation cavities, mechanical fixings, and layered assemblies associated with design for disassembly (DfD). In single-life assessments, higher mass generally correlates with increased embodied energy and, in some cases, increased embodied carbon.

However, results from Studies 2a, 3, and 4 demonstrate that material mass alone is not a reliable predictor of embodied carbon performance. Material type, carbon intensity, and biogenic carbon content significantly mediate the relationship between mass and GWP. Systems incorporating higher proportions of timber-based or straw-based materials exhibit lower embodied carbon despite greater mass, particularly when compared with mineral and petrochemical-based alternatives. This finding reinforces the importance of assessing material assemblies as integrated systems rather than relying on mass-based proxies.

At the same time, the results confirm that biobased substitution does not automatically yield carbon benefits. Where biogenic carbon release is assumed at end of life and reuse is not modelled, the apparent advantage of biobased materials may diminish or reverse. This highlights the importance of aligning material selection with realistic end-of-life and reuse strategies.

5.3. Tool and Dataset Sensitivity as a Central Finding

One of the most significant outcomes of this study is the magnitude of variation observed between LCA tools and databases when assessing the same physical system. Differences between the ICE database, Ubakus, and OneClick LCA result in divergent embodied carbon outcomes, even under similar system boundaries. These discrepancies arise from variations in background data, material carbon intensities, treatment of manufacturing energy, and biogenic carbon accounting conventions.

Rather than treating this variability as a weakness, the study deliberately exposes it as a structural characteristic of current LCA practice, particularly for emerging biobased construction systems where product-specific EPDs remain limited. The use of proxy datasets, while unavoidable in many cases, further amplifies uncertainty. The findings therefore support the argument that triangulation across tools and databases is essential when evaluating novel construction approaches, especially where results may inform design or policy decisions.

5.4. Design for Disassembly, Reuse, and Multi-Cycle Modelling

The study's multi-cycle analyses (Study 3b) demonstrate that the environmental potential of DfD-enabled modular systems is largely invisible under conventional single-life LCA frameworks. When future reuse is represented through multi-cycle allocation approaches, cumulative embodied carbon outcomes for modular systems improve substantially relative to single-use bonded solutions.

The magnitude of improvement varies with allocation method, reflecting different assumptions regarding responsibility for production impacts and quality retention across reuse cycles. Conservative approaches aligned with near-term policy contexts yield smaller but still meaningful reductions, while more explicitly circular allocation methods reveal greater long-term benefits. Importantly, these outcomes are method-driven representations rather than predictions of realised reuse, and depend on assumptions regarding recovery rates, logistics, and market acceptance.

This reinforces a key conceptual finding: LCA frameworks that assume demolition and material disaggregation at end of life systematically undervalue systems designed to remain intact and reusable. While uncertainties remain regarding actual reuse rates, excluding reuse scenarios entirely risks biasing assessment against circular design strategies at an early stage of adoption.

5.5. Biogenic Carbon Accounting and End-of-Life Assumptions

Results from the high-biobased new-build case (Study 4) clearly illustrate the influence of biogenic carbon accounting conventions on embodied carbon outcomes. Negative production-stage GWP values associated with biomass growth are offset by positive emissions at end of life under default incineration or disposal assumptions, resulting in a net positive cradle-to-grave GWP. These results are consistent with EN 15804 +A2 requirements and underline the distinction between temporary carbon storage and permanent sequestration.

The study does not challenge the validity of current standards but highlights their implications. In single-life LCAs, biogenic carbon storage offers limited benefit unless reuse, cascading use, or delayed release is explicitly modelled. For circular biobased systems, this creates a methodological disconnect between design intent and assessment outcome. While dynamic LCA approaches could better represent temporal effects, their limited standardisation restricts practical application.

5.6. Retrofit and New-Build Contexts: Interpreting Environmental and Circular Performance

The results presented in Section 4 reveal a clear divergence between the specific case retrofit and new-build applications in both environmental and circular performance, reflecting differences in physical constraints, material substitution potential, and assessment assumptions rather than contradictions in system behaviour.

In retrofit contexts, the modular over-cladding system is applied as an additional layer to an existing structure, limiting opportunities for deep structural optimisation. As a result, design-for-disassembly façades introduce additional framing, interfaces, fixings, and protective layers, increasing material mass and embodied impacts under single-life cradle-to-grave assessment. When evaluated at wall-element level, this material overhead can outweigh the embodied carbon benefits of incremental biobased substitution, particularly when standard end-of-life assumptions default to disassembly and material disaggregation rather than reuse.

These outcomes should not be interpreted only as a challenge for modular retrofit systems, but also as a reflection of assessment frameworks that privilege single-use performance. The multi-cycle results demonstrate that, when reuse across successive service lives is represented, cumulative embodied carbon outcomes shift materially in favour of modular systems. This indicates that the environmental rationale for modular retrofit is long-term and systemic rather than immediate, contingent on reuse pathways that extend service life beyond a single building intervention. However, efforts should be made to de-intensify modular system by both material mass and biobased solutions.

By contrast, the new-build application examined in this study exhibits a fundamentally different performance profile. The high-biobased modular wall system assessed in the Circ Reno case replaces a conventional heavyweight masonry assembly in its entirety, enabling extensive substitution of mineral and petrochemical materials with timber-based and straw-based components. Under single-life modelling, this substitution yields substantial embodied carbon reductions without relying on multi-cycle reuse assumptions.

From a circularity perspective, these findings suggest that retrofit represents a more complex circular challenge, where benefits depend on design for disassembly, durability, and the realisation of reuse across multiple life cycles. In such contexts, circular performance is not fully captured unless assessment frameworks explicitly accommodate reuse and allocation across service lives.

Importantly, the distinction observed between circular and single life performance also highlights a methodological issue. Conventional LCA practices that rely on single-life A1–C4 boundaries and default end-of-life scenarios can penalise circular systems while favouring material substitution strategies. This does not imply that circular retrofit solutions are environmentally inferior, but rather that their benefits lie outside the temporal scope of standard assessment.

Taken together, the results indicate that environmental and circular performance of modular façade systems must be interpreted in relation to application context. Retrofit and new-build systems address different decarbonisation challenges and require different assessment lenses. Failure to distinguish between these contexts risks both over-crediting material substitution in new-build and undervaluing reuse-oriented strategies in retrofit.

5.7. Implications for Practice and Policy

For practitioners, the findings suggest that biobased modular façades can offer significant long-term embodied carbon advantages, provided that design for disassembly is technically feasible and reuse pathways are considered early in design. Material selection should prioritise low-carbon intensity biobased products while minimising unnecessary structural complexity.

For policymakers, the results indicate that embodied carbon benchmarks based solely on single-life A1–C4 metrics may inadvertently discourage circular construction systems. Allocation approaches and reporting frameworks that recognise reuse and multi-cycle performance could better align regulatory instruments with long-term decarbonisation goals. At the same time, improved availability of verified EPDs for biobased materials remains a prerequisite for robust assessment.

5.8. Limitations and Scope of Interpretation

The results should be interpreted within the study’s defined scope and assumptions. Key limitations include reliance on proxy datasets for some biobased materials, uncertainty regarding real-world reuse rates and quality retention, and exclusion of dynamic temporal modelling. The physical cases analysed are derived from research prototypes and may not fully represent current market practice at scale.

Accordingly, the results are best understood as scenario-based representations that illustrate how methodological choices shape environmental outcomes, rather than as predictions of realised performance.

6. Conclusions

This paper has presented a comparative, multi-tool, and multi-cycle life-cycle assessment of biobased modular wall systems developed within two EU research and demonstration projects, benchmarked against conventional retrofit and new-build façade constructions. By combining empirical case data with explicit testing of methodological assumptions, the study contributes new evidence on how environmental and circular performance is represented—rather than merely achieved—within current LCA practice.

The results demonstrate that embodied carbon outcomes for modular façade systems are highly sensitive to modelling choices, including system boundaries, database selection, allocation methods, and treatment of biogenic carbon. Across retrofit cases, modular systems consistently exhibit higher material mass and, under single-life cradle-to-grave assessment, higher or comparable embodied carbon relative to lightweight bonded external wall insulation. These outcomes reflect the material overhead associated with prefabrication and design-for-disassembly strategies, as well as default end-of-life assumptions that do not accommodate reuse.

When multi-cycle allocation approaches are applied, however, cumulative embodied carbon outcomes for modular retrofit systems shift materially, with reductions of 21–45% observed across modelled reuse scenarios. While these results do not predict realised future reuse, they demonstrate that the environmental rationale for modular retrofit is primarily long-term and systemic, and that such systems are structurally undervalued by single-life LCA frameworks.

In contrast, the high-biobased modular system assessed in the new-build context exhibits substantial embodied carbon reductions under single-life modelling when compared with conventional masonry construction. This divergence highlights the importance of application context: new-build offers greater scope for deep material substitution and structural optimisation, whereas retrofit is constrained by existing buildings and relies more heavily on reuse potential to deliver long-term benefits.

A key conclusion of the study is that no single LCA result for biobased modular systems can be considered invariant or definitive. Apparent contradictions across studies—ranging from higher to lower embodied carbon relative to conventional solutions—are shown to arise from differences in modelling scope rather than from physical inconsistency. This underscores the need to align LCA methods with decision-making context and to avoid treating single-life cradle-to-grave assessments as universally applicable benchmarks, particularly for circular construction systems.

More broadly, the findings indicate that current LCA standards and tools are well suited to comparing linear, single-use construction systems but are less capable of representing design strategies explicitly intended for reuse, disassembly, and extended service life. Without explicit consideration of multi-cycle performance, circular systems risk systematic undervaluation at early stages of adoption, potentially discouraging innovation aligned with long-term decarbonisation goals.

This study does not claim to resolve uncertainties associated with biobased materials, reuse rates, or end-of-life pathways. Instead, it demonstrates the importance of transparent methodological framing, multi-tool triangulation, and scenario-based interpretation when assessing circular building systems. The results emphasise that environmental performance is not an intrinsic property of a construction system alone, but an outcome co-produced by design intent and assessment method.

Future research should prioritise the development of verified environmental datasets for emerging biobased materials, empirical monitoring of reuse and disassembly in practice, and further refinement of multi-cycle and temporal LCA approaches. At a policy level, assessment frameworks and embodied carbon benchmarks that recognise reuse-oriented systems will be necessary to support a transition from linear material flows toward buildings conceived as temporary material infrastructures capable of supporting multiple service lives.

Conflict of Interest

Author declared no conflict of interest.

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Appendix A

Case Studies

The physical case studies are primarily derived from prototype designs of biobased modular circular panel systems developed within two EU funded research projects; Drive 0 - which sought to accelerate decarbonisation of retrofit through modular circular retrofit solutions in social housing and Circ Reno - which sought to develop agri-crop biobased supply chains and solutions for application in modular retrofit. Several environmental LCA assessment (cases) were conducted on these by different researchers, covering diversity in biobased integration (low to high), different tools and data sets, and single and multiple life cycles, and forms the basis of the data in this research (*Drive 0*, 2023), (Circ Reno, 2023).

i) Physical Cases

Drive 0 - Retrofit (U Value 0.18 W/m2k– Combined Retrofit and Host Construction)

The Drive 0 project developed a modular circular system based on a light gauge steel frame (LGS) with biobased liner, studs and cement based outer cladding. LCA's examined two variations, a low biobased solution - a mineral wool insulation with natural binder and a mid-biobased –using wood fibre insulation batt. This system was compared to a conventional external wall insulation system based on EPS and acrylic render. This were designed to achieve combined retrofit and host wall target U values of 0.18 W/m²K, in line with new build standards, more than Irish retrofit regulations of 0.35 W/m²K. Fig. (**A1**) for 3D schematic of both systems.

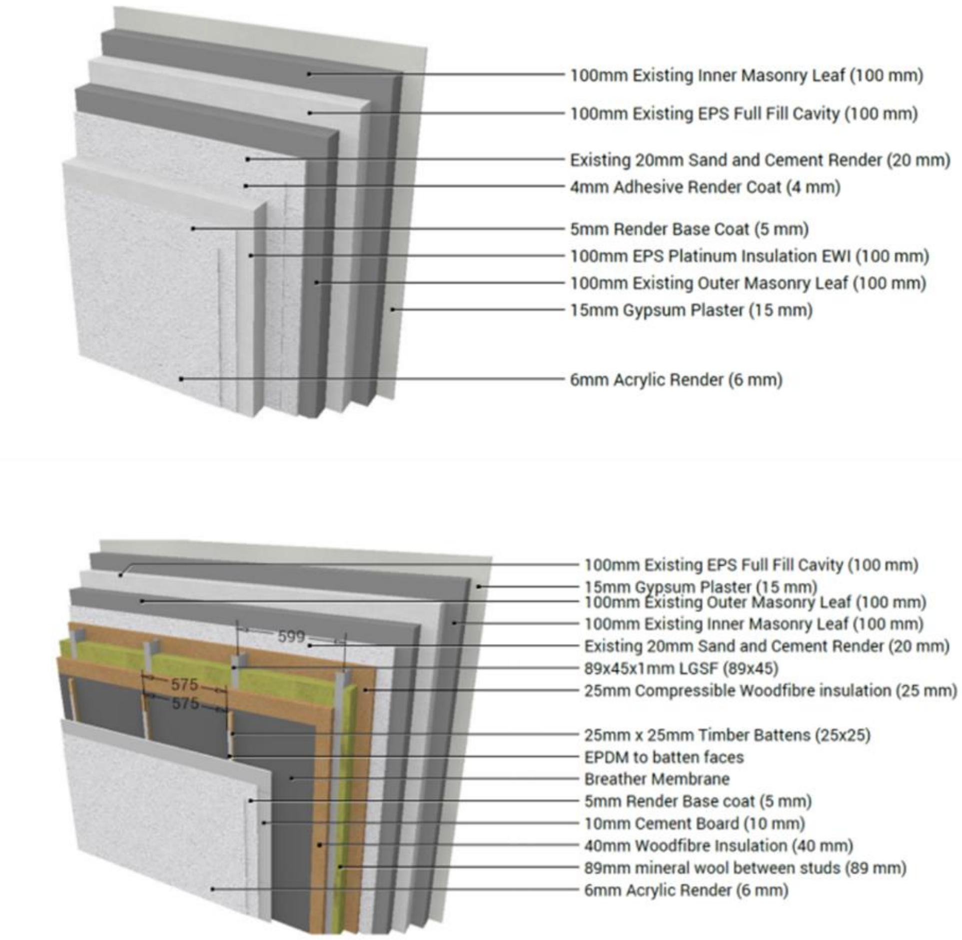


Figure A1: 3D schematic cutaways showing construction build-up of retrofit systems and host masonry cavity wall. (Kavanagh, 2025 [60]).

Modular Circular Panel *(Low and Mid Biobased)*

LGSF frame, 89 mm studs, with options of biobased fibre insulation batts or biobinder-mineral wool batts.

20mm compressible fibre insulation to rear, 40 mm external wood fibre insulative board, 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

Conventional External Wall Insulation (EWI)

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

Fig. (**A2**) showing schematic DfD concept for the Drive 0 Modular system with three levels of modular system hierarchy.

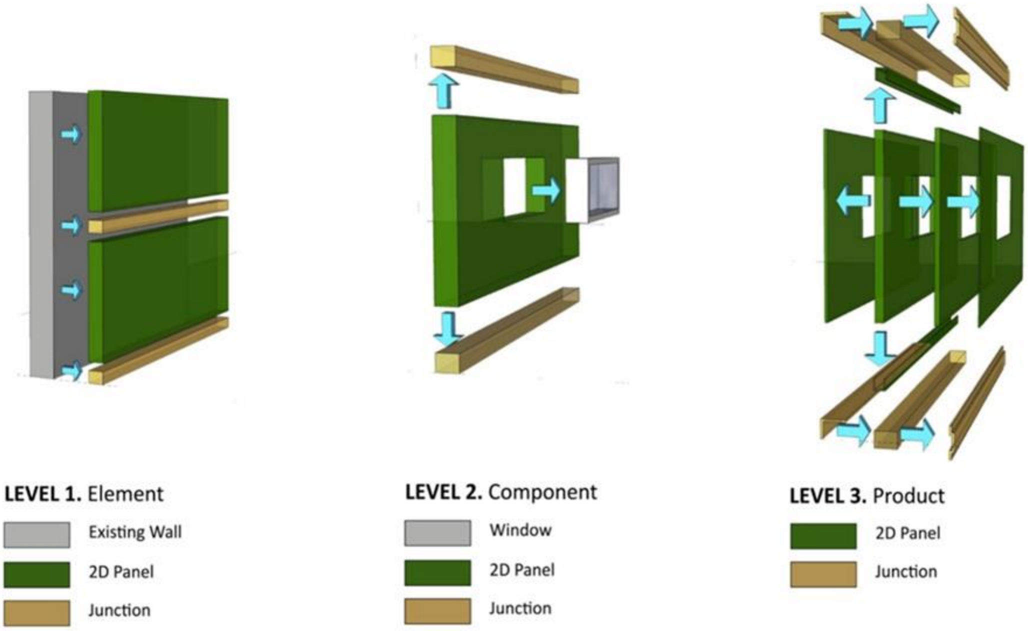
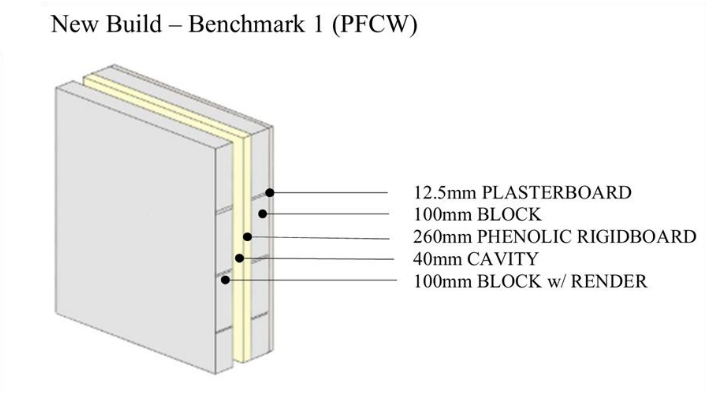


Figure A2: Modular system DfD hierarchy. Source Drive 0 Irish demonstrator. (Daly, 2023 [47]).

Circ Reno – New Build (U Value 0.14 W/m2k)

Circ Reno developed several prototype modular circular wall systems, involving extensive biobased material integration - timber stud framing, timber inner and outer linings, timber rainscreen battening and timber cladding (externally) with application of novel straw chip insulative infill. Several panel types were designed and assessed, including a proposed 'super insulated' new build twin stud modular wall system compared to conventional particle insulative fill masonry cavity wall construction at U value more than the German Passive Hus target of 0.15 W/m2k. Fig. (**A3**) showing schematic and build-up of Circ Reno modular systems.



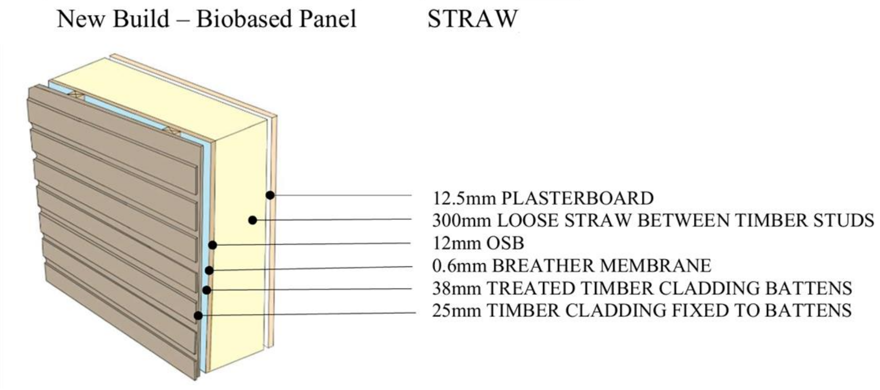


Figure A3: 3D Sketch showing construction build-up of Circ Reno (high -bio) biobased modular wall panels, Top – Single stud 150 mm (Internal), Bottom Twin Stud 220 mm (External). Source (O'Leary Aisling, 2026 [60])

Twin Stud 300 mm Biobased System

Structure: Timber studs, 300 m depth

Insulation: Straw-chip (high biobased) 300 mm

Internal Linings: Plasterboard internally

Ventilated façade: Timber battens + timber cladding externally

Fully mechanically fixed; high disassembly potential

U-value: 0.14 W/m²K

6-layer system

Conventional Partial Fill Cavity Masonry Wall System

Structure: 100mm masonry block inner and our leaf

Insulation: Phenolic rigid board in cavity 260mm

Internal Linings: Plasterboard internally

Façade: Rendered blockwork

Blockwork mortar bonded: low disassembly potential

U-value: 0.14 W/m²K

5-layer system

ii) Assessment Cases / Studies

Several environmental / LCA studies with circularity impacts were undertaken across these cases as follows:

Drive 0 – Retrofit

Study 1 Preliminary

A preliminary cradle to gate A1-A3 study was undertaken on EE / EC performance of the Drive 0 Modular system compared to conventional EWI based on the ICE database (for simplified early design stage and cross-national partner benchmarking)

Study 2 Comparative LCA's Tools

The second study involved two single life LCA assessments using two distinct tools / data bases, conducted on the Drive 0 (low bio) Modular system compared to conventional EWI based on Elemental Ubakus tool, which is based on mainly German EPD data sets, and the building level ONECLICK tool, which uses a different EPD library data set. Study 2a Elemental covered cradle to gate (A1-A3) and Study 2b was based on cradle to grave A1-A5, B4-B6, C1-C4.

Study 3 Comparative Single and Multi-Life LCA's

The third study comprised both a single life and several multi life cycle methods conducted on the Drive 0 (mid bio) Modular system compared to conventional EWI based using OneClick LCA. Study 3a Single Life was based on cradle to grave (A1-A5, B4-B6, C1-C4) (D for ref only), and Study 3b – Multi Life was based on cradle to grave (A1-A5, B4-B6, C1-C4 with D inclusive).

Circ Reno – New Build

Study 4 LCA of Straw Infill Modular Systems

The fourth study undertook single life LCA assessment of high bio modular system prototype with significant biobased integration and achieving passive standard U values of 0.14W/m2k in comparison to a similar thermal performance but radically different heavy weight masonry partial fill cavity wall construction. This study covered conventional assessment stages A1 – C4 using OneClick LCA tool.