A Flexible Life-Cycle Framework for Digital and Circular Net-Zero Construction

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Abstract. Achieving net-zero carbon performance in the built environment requires the integration of digital technologies, circular economy (CE) principles, and life-cycle-based decision-making. Despite advances in low-carbon materials and digital tools, the absence of holistic and adaptable frameworks often results in fragmented solutions with limited long-term impact. This paper presents a flexible life-cycle framework for digital and circular net-zero construction, developed through a structured synthesis of life-cycle assessment (LCA), circular design strategies, and digital information management approaches.

The framework supports consistent decision-making across the full asset life cycle, including design, construction, operation, adaptation, and end-of-life phases. It systematically maps life-cycle stages to key digital tools and circular decision points. Digital technologies—such as Building Information Modelling (BIM), life-cycle data environments, and decision-support systems—are positioned as integrative mechanisms enabling transparent assessment of carbon performance, material flows, and circular potential. This structure facilitates scenario-based comparison of alternative strategies under varying technological and regulatory conditions.

A key feature of the framework is its flexibility in accommodating evolving net-zero targets, policy requirements, and emerging technologies. Rather than prescribing fixed solutions, it supports adaptive pathways for renovation, reuse, repurposing, and long-term resilience. The framework is qualitatively assessed through consistency checks with established net-zero and CE principles, while empirical validation remains a direction for future research.

By aligning life cycle thinking with digital and circular strategies, this study provides a scalable methodological foundation and transferable insights for advancing net-zero construction.

Keywords: net-zero construction, life-cycle assessment, circular economy.

1 Introduction

The global construction sector accounts for approximately 38–40% of global energy-related CO_2 emissions, including both operational and embodied carbon [1, 2]. As operational efficiency improves, embodied carbon is increasingly dominant—representing up to 50–75% of total life-cycle emissions in high-performance buildings—demanding a shift toward whole-life carbon assessment [3, 4]. Achieving the 1.5°C climate target therefore requires a systemic transformation across the entire building life

cycle [5, 6]. Despite advances in low-carbon materials, circular design strategies, and digital technologies, current approaches remain fragmented [7, 8]. LCA is often applied retrospectively rather than as a proactive decision-support tool [9, 10]. CE principles remain inadequately connected to carbon accounting frameworks [11, 12]. Digital platforms provide data management capabilities without embedded sustainability decision logic [13, 14]. This fragmentation stems from a lack of coherent frameworks that integrate LCA, CE strategies, and digital technologies into a unified decision-making logic [15, 16]. Against this background, this study develops a flexible life-cycle framework for digital and circular net-zero construction, guided by four research questions: RQ1: How can LCA, CE, and digital technologies be integrated into a unified life-cycle framework?; RQ2: What are the key circular decision points and their operationalization mechanisms?; RQ3: How can the framework adapt to diverse contexts and evolving regulations?; RQ4: What are its theoretical and practical contributions?

This paper makes three main contributions. First, it proposes an integrated life-cycle framework that explicitly combines LCA, CE, and digital technologies across the full building life cycle, rather than treating them as separate or partially connected domains. Second, it operationalizes circularity through phase-specific decision points linked to EN 15978 modules, enabling circular strategies to be evaluated together with whole-life carbon performance. Third, it introduces a flexible, technology-agnostic workflow that supports scenario-based reasoning and adaptation to different project contexts, regulatory requirements, and levels of digital maturity.

2 Theoretical Background

2.1 Net-Zero Construction: Definitions and Frameworks

Net-zero building definitions have evolved from early operational energy concepts toward whole-life carbon accounting [6, 17]. Landmark studies confirm that operationally net-zero buildings can still carry substantial life-cycle carbon burdens: Jain and Rawal [18] found 866 tCO_2e over 60 years for an Indian net-zero energy building; Thiel et al. [19] reported a 10% higher global warming potential for a US net-zero building due to its photovoltaic system. EN 15978 provides the primary standard for whole-life carbon assessment, defining modules A1–A5 (product and construction), B1–B7 (use stage), C1–C4 (end-of-life), and D (beyond system boundary) [20]. ISO 14040/14044 governs the underlying LCA methodology [21]. Policy frameworks, including the EU Taxonomy and national net-zero strategies, are increasingly mandating whole-life carbon requirements [22]. Key ambiguities persist regarding temporal boundaries, biogenic carbon treatment, and the role of carbon offsets versus on-site reductions [23, 13].

2.2 LCA in Construction

LCA has become the principal method for evaluating environmental impacts of buildings across their lifespan [24]. The balance between embodied and operational carbon varies significantly by building type: Wang et al. [4] found that the production stage

accounted for 75.62% of emissions in a Chinese nearly-zero-energy building; Hu [25] reported 23% embodied carbon for a retrofit zero-energy building. Significant reductions are achievable—Kamel et al. [1] showed biobased materials achieving negative embodied carbon (−0.64 to −0.54 kg CO_2eq/m²a); Besana and Tirelli [7] demonstrated a 91% embodied carbon reduction through building reuse.

Persistent challenges include data availability for region-specific materials, retrospective rather than prospective application, and uncertainty in end-of-life scenarios [5, 26]. Dynamic models highlight the need for scenario-based approaches: Xin et al. [9] showed that Beijing's carbon peak by 2025 requires both renewable energy expansion and large-scale retrofit programs.

2.3 CE in the Built Environment

CE paradigm emphasizes closed-loop material flows, waste minimization, and value retention as an alternative to the linear model [27]. In construction, key strategies include design for disassembly (DfD), material passports, and urban mining [28, 29]. Eberhardt et al. [30] found DfD saves 15–21% in CO_2 emissions; Hai et al. [31] showed skeleton-infill design reduces embodied carbon by 45–55%. Secondary materials can substantially reduce embodied carbon, with business model innovations and public policies as critical enablers [32]. Barriers to adoption include regulatory systems aligned with linear processes, limited economic incentives, and fragmented supply chains [33, 34].

2.4 Digital Technologies for Sustainable Construction

BIM has emerged as the primary platform for integrating design, construction, and sustainability data [35, 36]. BIM–LCA workflows enable early-stage embodied carbon assessment: Alotaibi et al. [2] demonstrated a BIM-based method reducing baseline carbon from 414 to 135 kg CO_2e/m²/year through combined strategies. Digital twins extend BIM into the operational phase, linking models with real-time sensor data for predictive maintenance and adaptive management [37, 38]. Decision support systems (DSS) transform data into actionable insights, enabling scenario-based multi-criteria evaluation [39]. Material passports provide digital records enabling circular material flows and future reuse [40, 29]. Key challenges remain interoperability between platforms, data quality, and the digital maturity gap across the sector [8, 41].

2.5 Integrated Frameworks: State of the Art and Research Gaps

Recent studies increasingly highlight the need for integrated frameworks combining LCA, CE, and digital technologies [42, 43]. BIM–LCA integration has been widely explored [16, 44]. CE–LCA linkages have been demonstrated through approaches such as the Carbon Circularity Indicator [45]. Digital twin applications show promise for operational carbon monitoring [38, 37]. However, comprehensive frameworks integrating all three dimensions across the full life cycle remain scarce [46, 47]. Critical gaps include lack of flexibility for diverse building typologies and evolving net-zero

definitions; insufficient connection between digital platforms and circular decision-making; and limited whole-life perspective in existing tools [48, 49]. To better position the proposed framework within the existing body of research, **Table 1** summarizes the main characteristics and limitations of representative approaches identified in literature.

Table 1. Positioning of the proposed framework against existing approaches

Approach	LCA	CE	BIM /digital	Full life cycle	Decision workflow	Flexibility
BIM–LCA models	Yes	Limited	Yes	Partial	Limited	Medium
CE–LCA approaches	Yes	Yes	Limited	Partial	Limited	Medium
Digital twin sustainability models	Partial	Limited	Yes	Mainly operation	Medium	High
Proposed framework	Yes	Yes	Yes	Yes	Yes	High

3 Methodology

The methodology approach is grounded in systematic literature review principles and conceptual framework development methodologies [50, 51]. The unit of analysis comprises peer-reviewed literature, international standards, and policy documents related to LCA, CE, and digital technologies in construction. Sources were selected based on relevance to whole-life carbon assessment, circular strategies, and digital integration, with emphasis on recent studies and established standards (e.g., EN 15978, ISO 14040/14044). In addition, insights from ADiCu project activities, including market analysis and stakeholder interactions, informed the identification of key decision points and practical constraints, particularly regarding the integration of CE principles and BIM-enabled workflows [52]. Validation is conducted through qualitative consistency assessment. The framework development is based on a structured literature synthesis across five domains: LCA and whole-life carbon, net-zero standards and policy, CE strategies, digital technologies, and integrated decision-support frameworks. The synthesis involved identifying key concepts, mapping interrelations, conducting gap analysis, and extracting design principles.

4 The Proposed Framework

4.1 Framework Overview and Principles

The proposed framework integrates LCA, CE strategies, and digital technologies into a coherent structure for net-zero construction decision-making. It is organized around four core principles: integration (carbon assessment, circular strategies, and digital tools treated as interdependent); transparency (data-driven, traceable decision-making across all phases); flexibility (adaptable to evolving targets, regulations, and technologies); and whole-life perspective (covering all modules A1–D per EN 15978).

The conceptual architecture of the framework is illustrated in **Fig. 1**, presenting three interrelated layers that structure the system.

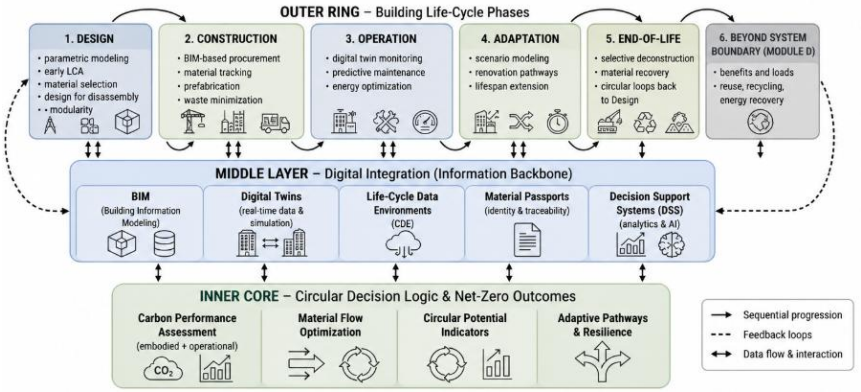


Fig. 1. Conceptual Architecture of the Integrated Life-Cycle Framework

The **outer layer** represents the building life cycle, structured into five phases: design, construction, operation, adaptation, and end-of-life. The **middle layer** defines the digital integration backbone, including BIM, digital twins, life-cycle data environments, material passports, and decision-support systems. The **inner core** introduces circular decision logic, linking carbon performance assessment, material flow optimization, circularity indicators, and adaptive pathways for long-term resilience.

Fig. 2 presents the proposed framework as a life-cycle decision workflow integrating BIM, LCA, and circular economy principles. Digital technologies support data integration, performance monitoring, and scenario analysis, while circular decision points guide key decisions across design, construction, operation, and end-of-life stages. Through scenario comparison and continuous feedback, the framework enables adaptive decision-making and supports integrated net-zero and circular construction across the building life cycle.

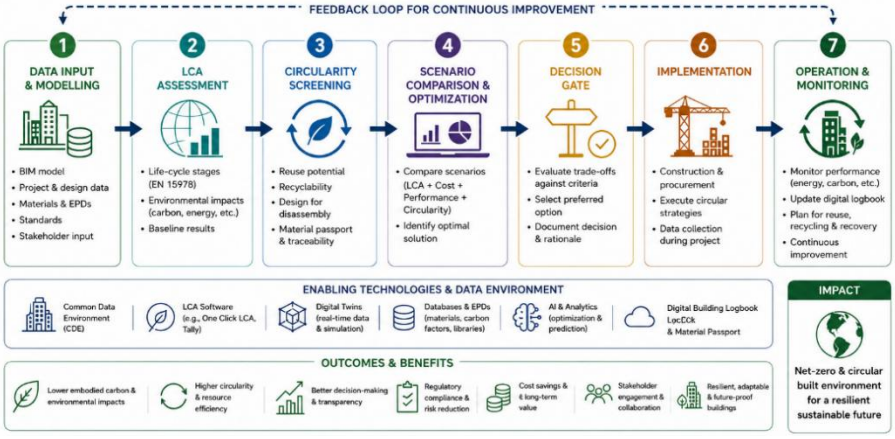


Fig. 2. Integrated BIM–LCA–Circular Framework Overview Diagram

4.2 Framework Components: Phase Mapping, Digital Layer, and Circular Logic

The five life-cycle phases map directly to EN 15978 assessment modules: the design phase establishes the baseline for modules A1–A5 (product and construction stages); the construction phase monitors A4–A5 execution; the operation and maintenance phase tracks modules B1–B7 (use stage); the adaptation phase informs renovation scenarios within module B5; and the end-of-life phase covers modules C1–C4 (deconstruction, transport, waste processing, disposal) and Module D (benefits and loads beyond the system boundary). This explicit module assignment ensures consistency with standardized LCA reporting and enables comparative benchmarking across projects. The digital integration layer relies on interoperability standards to maintain data continuity across tools and phases. BIM serves as the central data backbone, maintaining a structured, updatable model of the asset throughout its life cycle [35, 36]. Life-cycle data environment ensures seamless exchange between BIM, LCA tools, and material databases via open standards such as IFC and ISO 19650 [38]. Digital twins extend the BIM model into the operational phase, integrating real-time sensor data for performance monitoring and predictive analytics [37]. Material passports provide persistent digital records of material composition, enabling informed decisions at adaptation and end-of-life stages [29, 40]. DSS synthesize data from all layers to enable scenario-based reasoning and multi-criteria comparison of design and operational strategies [39]. The framework is designed to be technology-agnostic, allowing substitution of specific digital tools as capabilities evolve while maintaining the underlying assessment logic. This ensures long-term applicability and resilience across diverse project contexts and levels of digital maturity.

4.3 Alignment with Net-Zero Principles, CE, and Digital Integration Principles

The framework's consistency with established principles was assessed across three dimensions. Against net-zero construction principles, the framework adopts a whole-life carbon perspective covering all EN 15978 modules (A1–D), addresses both embodied and operational carbon, and supports scenario-based comparison of decarbonization strategies. Against CE principles [27], circular decision points operationalize the three CE principles—designing out waste, keeping materials in use, and regenerating natural systems—across all life-cycle phases. Material passports and end-of-life recovery loops directly support closed-loop material flows. Against digital integration requirements, the framework relies on open standards for interoperability, positions digital technologies as enablers rather than prescriptive tools, and maintains data traceability across phases.

4.4 Framework Applicability, Strengths, and Limitations

The proposed framework is among the first to explicitly integrate life-cycle assessment (LCA), circular economy (CE) principles, and digital technologies across all EN 15978 life-cycle phases (A–E) through operationalized circular decision points. By combining life-cycle phase mapping, digital integration, and circular decision-making within a single structure, it addresses the fragmentation commonly observed in existing approaches and provides a high degree of comprehensiveness and operational applicability.

The practical applicability of the framework can be illustrated through the renovation of an existing public office building. In the planning stage, a BIM model is linked to material databases and environmental product declarations (EPDs), enabling life-cycle assessment of the product and construction stages (A1–A5) together with selected operational impacts (B phase). Circularity screening is then used to evaluate alternatives such as façade replacement, reuse of existing façade elements, and the introduction of material passports. These options are compared using environmental, circularity, cost, and performance criteria, allowing transparent assessment of trade-offs between embodied carbon reduction, value retention, and technical feasibility. Based on this comparison, the preferred solution is selected and documented, while operational monitoring provides feedback for future adaptation and end-of-life planning.

However, as a conceptual framework, empirical validation is still required to confirm its effectiveness in practice. Its implementation depends on data availability and organizational digital maturity, while full application may be challenging for stakeholders with limited BIM or LCA capabilities. Further development of uncertainty quantification methods would strengthen robustness in scenario-based decision-making.

5 Discussion

5.1 Theoretical Contributions

This study addresses a persistent gap in literature: the absence of frameworks that simultaneously integrate LCA, CE strategies, and digital technologies across the full building life cycle. Existing approaches address these dimensions in isolation or in partial pairings [45, 38, 16], leading to fragmented outcomes confirmed by recent reviews [53, 54]. The framework makes three theoretical contributions. First, it repositions digital technologies—particularly BIM and digital twins—not merely as data management tools but as active enablers of circular decision-making and transparent carbon assessment. Second, the introduction of explicit circular decision points provides a structured mechanism for operationalizing CE principles at each life-cycle phase, bridging the gap between conceptual CE frameworks and actionable construction practice. Third, the framework's flexibility mechanisms—scenario-based reasoning, technology-agnostic design, and adaptive pathways—address the critical limitation of rigidity identified in existing integrated frameworks [48, 49].

5.2 Practical Implications and Future Directions

For designers and engineers, the framework provides structured guidance for integrating LCA and circular strategies from the earliest design stages, supporting informed material selection, DfD, and scenario comparison before commitments are made. For contractors and material suppliers, it identifies opportunities to reduce embodied carbon through procurement decisions and material tracking, with material passports enabling future reuse. For asset owners and facility managers, the digital twin integration supports operational optimization and evidence-based adaptation decisions. For policymakers, the framework's alignment with EN 15978, ISO 14040/14044, and the EU Taxonomy provides a basis for regulatory integration and the development of whole-life carbon reporting requirements. In comparison with existing approaches, the proposed framework extends BIM–LCA models by incorporating circular decision points and adaptive pathways; extends CE–LCA linkages by embedding them within a digital integration layer; and extends digital twin applications by connecting operational monitoring to whole-life carbon assessment and end-of-life planning.

Future research should focus on: (1) empirical validation through case studies and pilot implementations across building typologies; (2) development of digital tools that operationalize the framework's decision logic; (3) advancement of embodied carbon databases and material tracking infrastructure; (4) uncertainty quantification methods for scenario-based reasoning; and (5) integration with emerging policy frameworks to support large-scale adoption.

6 Conclusion

This paper presents a flexible life-cycle framework that integrates life-cycle assessment (LCA), circular economy (CE) principles, and digital technologies to support net-zero construction. By combining life-cycle phase mapping, digital integration, and circular decision points, the framework provides a structured decision-making approach applicable across the building life cycle.

The framework contributes to existing research by linking environmental assessment, circularity, and digital information management within a single adaptable structure. It supports phase-specific decision-making while remaining applicable across different building types, project contexts, and levels of digital maturity. The qualitative assessment indicates alignment with net-zero construction requirements, CE principles, and digital integration objectives. As the construction sector accelerates its transition toward sustainability, the proposed framework offers a practical foundation for implementing integrated net-zero and circular construction strategies.

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