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

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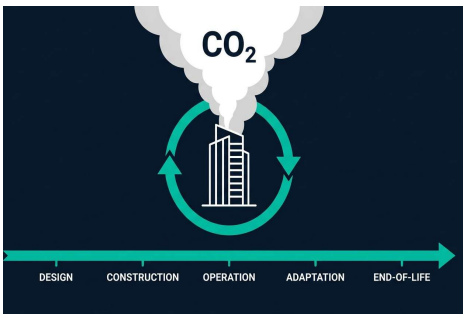
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The Challenge: Construction & Climate



1.5°C
Paris Agreement target requiring sector-wide transformation

38-40%
of global CO2 emissions from the built environment

50-75%
embodied carbon share in high-performance buildings

- The built environment is responsible for a disproportionate share of global greenhouse gas emissions — yet the sector lacks integrated tools to address this challenge across the full building life cycle.

Pomponi & Moncaster, 2016 | Huang et al., 2018 | IPCC, 2022

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The Fragmentation Problem

- Existing approaches address sustainability in isolation — none provide an integrated, life-cycle-wide decision framework.

ISSUE 1

LCA: Retrospective & Disconnected

Life Cycle Assessment is typically applied post-design, as a verification tool rather than an active decision driver embedded throughout all phases.

Result: missed optimization opportunities in early design

ISSUE 2

Circular Economy: Principles Without Operationalization

CE strategies (reuse, DfD, material passports) exist as concepts but lack explicit integration into project decision gates and LCA workflows.

Result: circularity remains aspirational, not actionable

ISSUE 3

Digital Tools: Platforms Without Logic

BIM, digital twins, and DSS operate as data repositories without systematic linkage to carbon performance assessment or circular decision-making.

Result: data richness without decision intelligence

Hossain et al., 2020 | Boje et al., 2020 | Elghaish et al., 2021

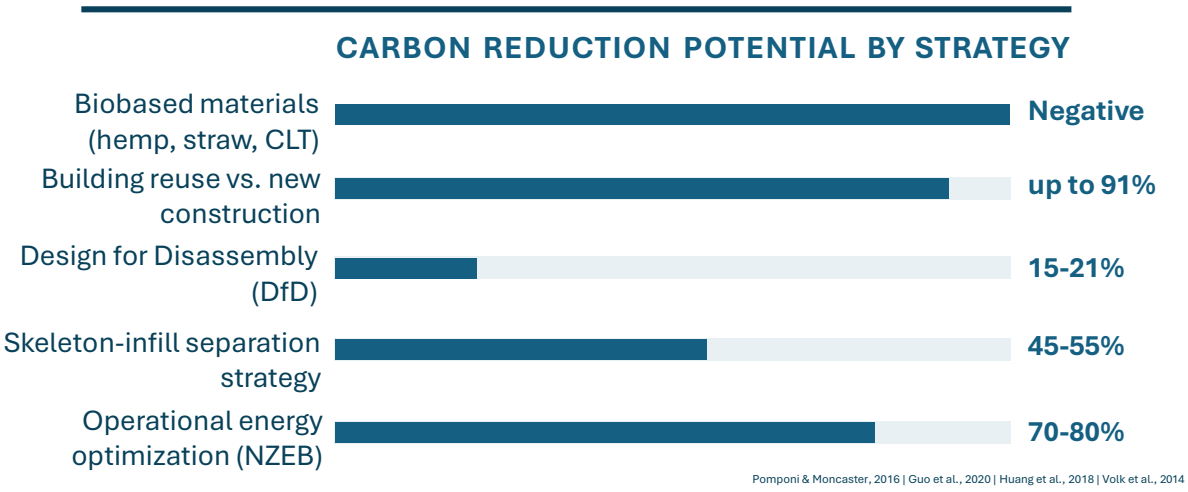
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Research Questions

RQ1	RQ2	RQ3	RQ4
INTEGRATION	• **OPERATIONALIZATION**	• **DIGITAL ENABLEMENT**	• **FLEXIBILITY**
• How can LCA, CE principles, and digital technologies be systematically integrated into a single coherent life-cycle framework?	• How can circular economy strategies be operationalized as explicit decision gates embedded within each life-cycle phase?	• What role do BIM, digital twins, material passports, and DSS play as active enablers — not passive data stores — of net-zero decision-making?	• How can the framework remain adaptable across diverse building types, regulatory contexts, and levels of digital maturity?

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LCA Evidence: What the Literature Shows



Pomponi & Moncaster, 2016 | Guo et al., 2020 | Huang et al., 2018 | Volk et al., 2014

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Digital + Circular Literature: State of the Art

Digital Technologies

BIM-LCA Integration
IFC-based data exchange enables automated carbon quantification at design stage (LOD 300-500)

Gap: no link to circular decision logic

Digital Twins
Real-time sensor data + simulation enables operational monitoring and predictive maintenance

Gap: rarely extended to end-of-life planning

Decision Support Systems
Multi-criteria analysis (LCA + cost + performance) supports scenario-based design optimization

Gap: not embedded in life-cycle phases

Circular Economy

Material Passports
Digital records of material composition enabling recovery at end-of-life; EU regulatory push (ESPR)

Gap: not linked to LCA data environments

Design for Disassembly
15-21% embodied carbon reduction potential; requires early-stage circular decision gates

Gap: no standardized decision criteria

Circularity Indicators
ISO 14040, EN 15978 Module D, EU Taxonomy — alignment requires systematic phase mapping

Gap: fragmented across standards

Boje et al., 2020 | Elghaish et al., 2021 | Firoozi & Firoozi, 2022 | Massafra et al., 2023

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Methodology

- A five-step design science research approach combining systematic literature synthesis with framework construction and qualitative validation.
- Technology-agnostic design: framework applicable across building types, regulatory contexts, and levels of digital maturity

1 Systematic Literature Review
- LCA, circular economy and digital technologies
- EN 15978, ISO 14040 and ISO 19650

02 Gap Analysis
- Identify fragmentation across the three domains
- Map opportunities for integration

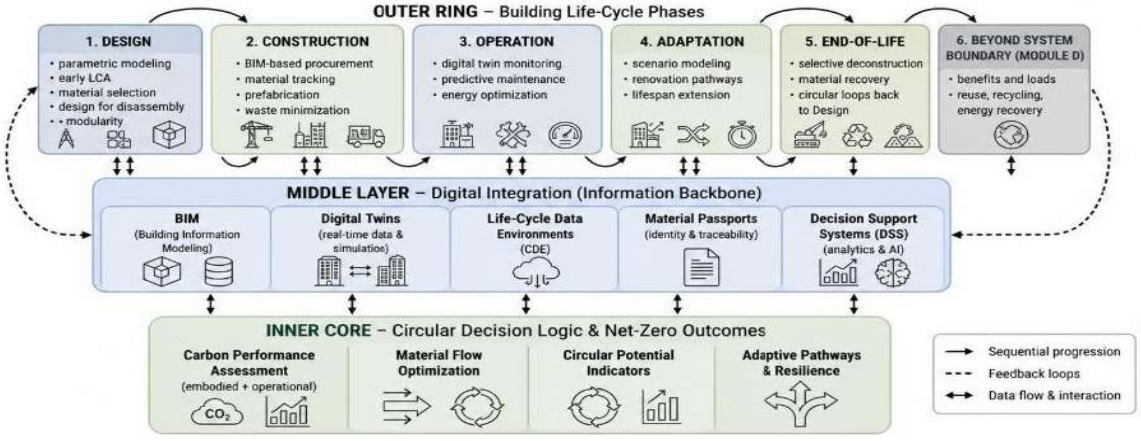
03 Framework Construction
- Develop the three-layer architecture
- Life-cycle phases, digital integration and circular decision logic

04 Phase Mapping
- Assign EN 15978 modules A1–D to life-cycle phases
- Map digital tools and circular strategies to each phase

05 Qualitative Assessment
- Evaluate consistency with net-zero principles
- Evaluate circular economy and digital integration criteria

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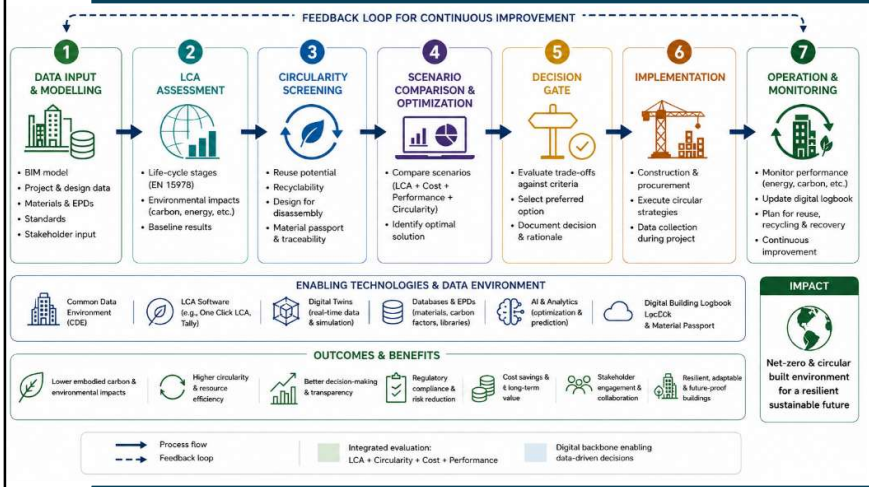
Framework Architecture



Sustainability is achieved through continuous interaction between life-cycle processes, data environments, and decision mechanisms.

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Operational Logic: 6 Process Stages



6 OPERATIONAL STAGES

>Define & Plan
>Model & Quantify
>Evaluate & Optimize
>Integrate & Decide
>Implement & Monitor
>Operate & Circulate

Nahod, 2026 | Massafra et al., 2023 | Elghaish et al., 2021

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Phase Mapping: EN 15978 Modules, Digital Tools & Circular Strategies

Life-Cycle Phase	EN 15978 Modules	Digital Tools	Circular Strategies
1. Design	A1–A5	BIM (LOD 300–500), LCA tools, DSS	Design for disassembly (DfD), material selection, early LCA, modularity
2. Construction	A4–A5	BIM-based procurement, material tracking	Waste minimization, prefabrication, material passport creation
3. Operation	B1–B7	Digital twins, real-time monitoring, DSS	Energy optimization, predictive maintenance, lifespan extension
4. Adaptation	B5	Scenario modeling, LCA data environments	Renovation pathways, circular loops back to the design phase
5. End-of-Life	C1–C4 + D	Material passports, digital building logbook	Selective deconstruction, material recovery, reuse, recycling

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Digital Integration Layer: 5 Active Enablers

Acronym	Digital Tool	Role in the Framework	Related Standards and Policies
BIM	Building Information Modeling	Central data backbone: a structured, updatable asset model throughout the building life cycle (LOD 300–500).	IFC; ISO 19650
DT	Digital Twins	Combine sensor data and simulation for operational monitoring, predictive analytics and end-of-life planning.	ISO 23247
LCA	LCA Data Environments	Enable data exchange between BIM, LCA tools and material databases through open standards.	EN 15978; ISO 14040
MP	Material Passports	Maintain digital records of material composition to inform adaptation, reuse and end-of-life decisions.	EU ESPR; ISO 59004
DSS	Decision Support Systems	Compare scenarios using life-cycle impacts, cost, performance and circularity; may support AI-assisted optimisation.	ISO 14040; EU Taxonomy

Boje et al., 2020 | Elghaish et al., 2021 | Massafra et al., 2023 | Toprak, 2024

Circular Decision Points: The Novel Mechanism



- **Design:** Material selection, design for disassembly (DfD) assessment and modularity targets.
- **Construction:** Material passport creation and a waste minimisation decision gate.
- **Adaptation:** Scenario comparison and optimisation of circular value.
- **End-of-Life:** Recovery pathways, component reuse and Module D accounting.
- **Core contribution:** A framework that translates circular economy principles into explicit decision gates across the EN 15978 life-cycle phases.

Nahod, 2026 | Hossain et al., 2020 | Firoozi & Firoozi, 2022

Qualitative Assessment Results

CRITERION SET 1	CRITERION SET 2	CRITERION SET 3
Net-Zero Principles	**Circular Economy Integration**	**Digital Integration**
>Full EN 15978 module coverage (A1-D)	>CE principles operationalized at each phase	>BIM-LCA-CE data flow via IFC/ISO 19650
>Embodied + operational carbon integration	>Material passport linkage throughout	>Digital twins extend to end-of-life
>Module D beyond-boundary accounting	>DfD and reuse pathways embedded	>DSS enables multi-criteria decisions
>Scenario-based carbon optimization	>Circularity indicators aligned with EU Taxonomy	>Technology-agnostic scalability

Nahod, 2026 | EN 15978:2011 | ISO 14040:2006

Three Theoretical Contributions

Digital Technologies as Active Enablers

- Reconceptualizes BIM, digital twins, and DSS from data repositories to active decision-intelligence systems embedded within each life-cycle phase.
  - *Extends existing BIM-LCA integration frameworks to include circular decision logic*

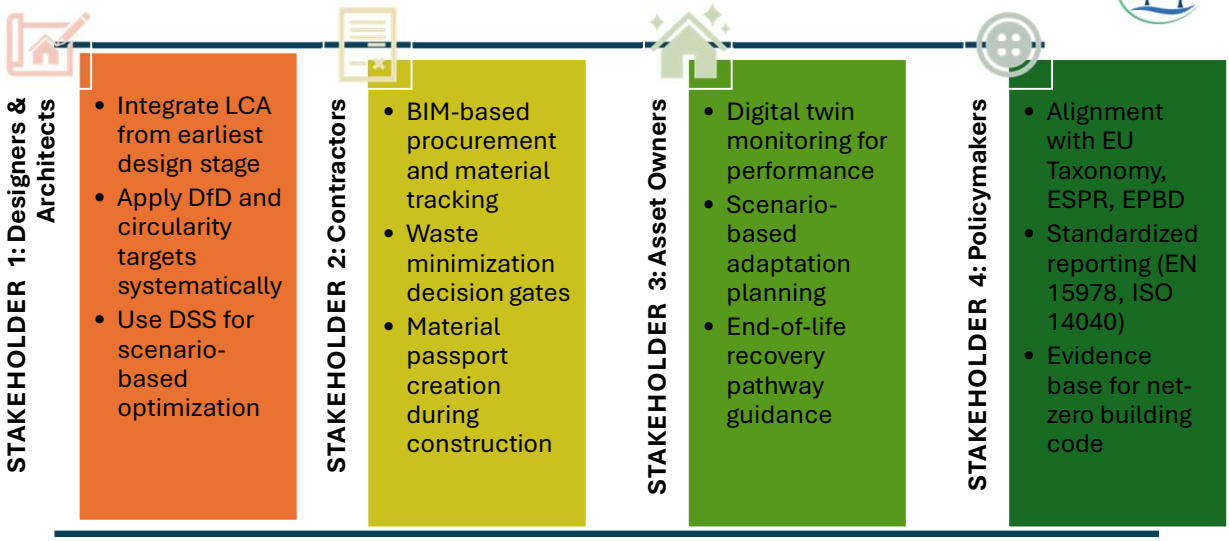
Circular Decision Points Operationalized

- First framework to translate CE principles (DfD, material passports, reuse) into explicit, mandatory decision gates at every EN 15978 life-cycle stage.
  - *Bridges the gap between CE theory and actionable project decision-making*

Flexibility Mechanisms Addressing Framework Rigidity

- Technology-agnostic, scalable architecture accommodates diverse building types, regulatory environments, and digital maturity levels without loss of rigor.
  - *Addresses the scalability gap identified across previous integrated frameworks*

Practical Impact: Who Benefits



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How This Advances the State of the Art

Domain	Prior State of the Art	This Framework's Advance
BIM-LCA Integration	IFC-based carbon quantification at design stage; limited to modules A1-A5	Extends BIM-LCA across all EN 15978 phases (A1-D) with circular decision logic at each stage
CE-LCA Connection	CE strategies studied in isolation; no systematic link to LCA workflows or decision gates	Operationalizes CE as explicit decision points embedded within each life-cycle phase — first such integration
Digital Twins in Construction	Operational monitoring and predictive maintenance; rarely extended beyond Phase 3	Digital twins connected to end-of-life planning, material passport updates, and Module D recovery
Framework Flexibility	Most frameworks are tool-specific or building-type-specific; limited scalability	Technology-agnostic architecture scalable across building types, regulations, and digital maturity levels

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Conclusion & Future Research

- This paper presents the first integrated framework to simultaneously address LCA, circular economy, and digital technologies across all EN 15978 life-cycle phases — bridging the fragmentation gap that has limited net-zero construction progress.

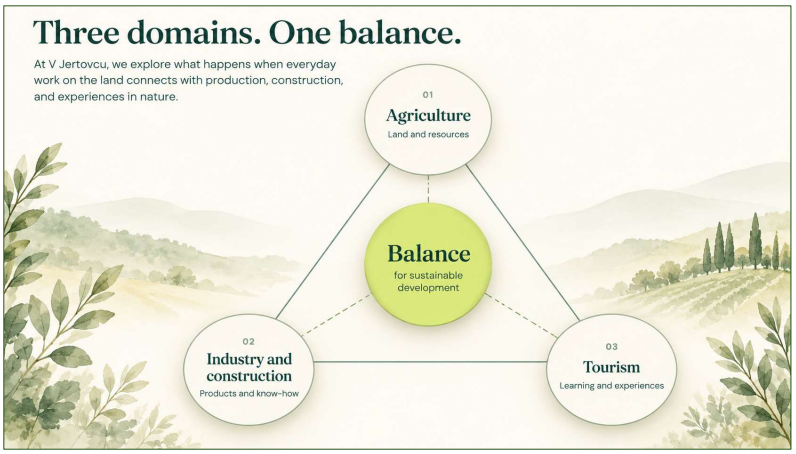
Future Research Priorities

- Empirical validation through case studies across building types and climates.
- Development of quantitative circularity metrics aligned with the EU Taxonomy and ISO 59004.
- Integration of AI-enhanced decision support systems for scenario optimisation.
- Testing IFC-based data exchange between LCA and circularity tools.
- Analysis of alignment with the EPBD, ESPR and national net-zero building regulations.

The three-layer architecture, six operational stages, and explicit circular decision points provide a scalable, technology-agnostic structure for evidence-based, life-cycle-wide decision-making.

From research to a small living experiment

- **V Jertovcu, Croatia**
- Agriculture: land and resources
- Construction: products and know-how
- Learning and nature experiences



From the paper to practical guidance

- A short guide for construction businesses on Europe's evolving product data rules and actions they can take now.
- Now available on Amazon Kindle



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ADiCu

Agile Digitalization for Circular Construction: Unraveling the End of Projects

UIP-2025-02-2415 | Croatian Science Foundation | 2026 – 2031 (5 years)

KEY RESEARCH QUESTION

What happens to materials, information and value when a construction project is formally finished?

CIRCULAR DECISIONS
Design, construction, operation and end-of-life for continuous material and value flows.

DIGITAL CONTINUITY
BIM, life-cycle data and interoperable information across the asset life cycle.

VALUE BEYOND HANDOVER
New business models, public procurement and policy support for a circular and resilient built environment.



ADiCu Kick-off Workshop | University of Zagreb | July 2026

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Thanks for your kind attention!
Any questions from the audience?
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3RD INTERNATIONAL CONFERENCE ON NET-ZERO BUILT ENVIRONMENT
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PROFESSIONAL PROFILE
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