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# From Waste to Resource: Implementing Circular Economy Principles in Prefabricated and Conventional Construction

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## Abstract

*This article synthesizes established and emergent approaches for embedding circular economy principles into the built environment through design-for-change, prefabrication, reuse of construction and demolition waste (CDW), and collaborative procurement models. It draws exclusively upon a curated set of empirical case studies, methodological critiques, materials science findings, lifecycle assessment (LCA) literature, procurement and project-delivery research, and contemporary conceptual analyses. The structured abstract outlines the background, aims, methods, principal findings, and implications.*

*Background: The built environment is a major consumer of raw materials and producer of waste; transitioning buildings and construction systems towards circularity requires multidimensional interventions across design, material selection, manufacturing, procurement, and end-of-life strategies (Geissdoerfer et al., 2017; Kirchherr et al., 2017).*

*Aims: This paper aims to generate an integrated framework for implementing circular economy principles in prefabricated and conventional construction by synthesizing evidence on recycled-material prefabrication, deconstruction economics, lifecycle impacts, collaborative technologies, procurement models, and policy barriers.*

*Methods: A qualitative integrative analysis was performed using the provided literature as primary data. The analysis combines theoretical elaboration, cross-comparison of case studies (deconstruction and prefabrication), critical review of LCA simplifications, and interpretation of socio-organizational drivers and barriers, synthesizing findings into actionable recommendations.*

*Results: Three co-evolving intervention domains emerged: (1) material- and component-level strategies emphasizing modularity, reversibility, and recycled CDW incorporation; (2) process and digital strategies including Building Information Modeling (BIM) and collaborative technologies to support material traceability and circular procurement; and (3) governance and procurement mechanisms—relational contracting, integrated project delivery, and circular public procurement—necessary to align incentives. Empirical evidence shows recycled CDW can be used effectively in hybrid composites and prefabricated systems with careful engineering, yet LCA outcomes are sensitive to methodological simplifications and boundary choices (Keskisaari et al., 2016; Kellenberger & Althaus, 2009).*

*Implications: Implementation requires technical standardization, revised procurement frameworks to internalize lifecycle benefits, investments in deconstruction capabilities, and cross-disciplinary collaboration. Limitations include variability in CDW composition, market immaturity, and policy fragmentation.*

*Conclusion: A systems approach uniting technical innovation with procurement reform and collaborative technologies can significantly advance circularity in construction. The article offers detailed design strategies, procurement pathways, and research priorities to accelerate the transition.*

## Keywords

*circular economy, prefabrication, construction and demolition waste, deconstruction, lifecycle assessment, procurement, Building Information Modeling.*

## INTRODUCTION

The global construction sector stands at a crossroads where the traditional linear extract-manufacture-build-dispose paradigm is increasingly unsustainable. Buildings account for substantial resource consumption, embodied energy, and waste generation—pressures that intensify as urbanization and infrastructure renewal accelerate (Geissdoerfer et al., 2017). The circular economy presents a paradigmatic alternative that prioritizes material retention, reuse, and system-level redesign to decouple economic value from raw resource extraction (Kirchherr et al., 2017). Within the built environment, implementing circularity requires far more than isolated recycling initiatives; it necessitates redesigning building components, procurement models, and collaborative practices to support reuse, reversibility, and material traceability (Debacker et al., 2017; Minunno et al., 2018).

Despite conceptual clarity and growing policy interest, multiple persistent gaps hinder broad adoption. These include technical challenges in integrating recycled construction and demolition waste (CDW) into prefabricated systems, incomplete or inconsistent lifecycle assessment methodologies that obscure trade-offs, institutional procurement practices that favor lowest-first-cost solutions, and socio-organizational barriers such as limited awareness and collaboration deficits among stakeholders (Kirchherr et al., 2018; Amudjie et al., 2023). Moreover, sector-specific evidence on scalable prefabrication systems using recycled feedstocks remains nascent, yet promising experiments suggest prefabricated modular components can accelerate circular material flows if deliberately designed for disassembly and material quality retention (Pecur et al., 2014; Minunno et al., 2018).

This research positions itself at the intersection of material innovation and project delivery. It adopts the role of a Lead Academic Researcher and Senior Editor to produce a comprehensive synthesis that addresses the following objectives: (1) examine material- and design-level strategies for reusing CDW within prefabrication; (2) analyze lifecycle assessment concerns and evidence regarding environmental outcomes of circular interventions; (3) identify governance, procurement, and collaboration mechanisms that enable circular practices; and (4) propose an integrated, actionable framework for practitioners and policymakers. The synthesis relies exclusively on the provided literature, combining empirical findings and theoretical propositions into an extended, detailed narrative aimed at academic and professional audiences.

The problem statement is threefold: first, while circular principles are widely advocated, there is diffuse and sometimes contradictory evidence about how to apply them operationally in construction projects (Kirchherr et al., 2017); second, prefabrication and modular building offer potential accelerants for circularity, but integrating recycled CDW at scale faces materials, manufacturing, and market barriers (Minunno et al., 2018; Pecur et al., 2014); and third, conventional procurement and contracting arrangements disincentivize investments in deconstruction, materials tracing, and product-as-service solutions (Matthews & Howell, 2005; Lingegård et al., 2021). The literature gap that this article addresses is practical synthesis—sembling the technical, assessment, and governance evidence into a coherent set of strategies that can inform implementation and future investigation.

## METHODOLOGY

Given the directive to synthesize only the provided references, the research approach adopted is a rigorous qualitative integrative review and theoretical elaboration. The method is deliberately text-based and analytic rather than empirical: it interprets case studies, LCA methodological analyses, materials science findings, procurement studies, and conceptual pieces to generate a systems-level framework. The methodology consists of four analytical steps.

First, systematic extraction and categorization of themes. Each reference was reviewed for primary claims, methods, and contextual details. Themes were coded into clusters: material innovation (e.g., recycled CDW composites), design-for-change and disassembly, LCA and methodological critiques, procurement and contracting models, collaborative technologies (e.g., BIM), deconstruction economics, and socio-organizational drivers/barriers. This clustering allowed cross-referencing of domains where technical and governance issues overlap.

Second, cross-case synthesis. Empirical case studies and experiments (e.g., deconstruction case in Southern Italy, prefabricated recycled systems, hybrid composites) were compared to identify recurring success factors, constraints, and transferable lessons. Comparative attention focused on technical feasibility, economic viability, environmental impact claims, and scalability.

Third, methodological critique and harmonization. LCA-focused literature was examined to understand sensitivity to simplifications, system boundaries, and end-of-life assumptions—an essential step because lifecycle claims underpin many circularity arguments (Kellenberger & Althaus, 2009; Erlandsson & Borg, 2003). The review assessed how differences in methodological choices influence conclusions about the environmental superiority of reuse, recycled-content products, and prefabrication strategies.

Fourth, constructivist synthesis into an integrative framework. The insights from material, process, and governance clusters were synthesized into a set of recommendations and a proposed framework that aligns technical design strategies with procurement reforms and collaborative technologies. The framework emphasizes multi-stakeholder alignment, transparency, and iterative learning.

Throughout the methodology, assertions were cross-validated with at least one supporting reference to ensure claims are anchored in the provided literature. The integrative approach privileges depth of explanation and cross-domain linkage over summarization, delving into theoretical implications, counter-arguments, and uncertainties.

## RESULTS

The synthesis yields three primary domains of results: material- and component-level strategies; process-level and digital enablers; and governance and procurement mechanisms. For each domain, detailed findings, contextual nuances, and supporting evidence are described.

### Material- and component-level strategies

**Design for change and reversibility.** A consistent theme in the literature is that buildings should be designed with future change and material recovery in mind (Debacker et al., 2017; Minunno et al., 2018). Design for change includes modularity, reversible connections, and standardized interfaces that enable components to be disassembled, inspected, upgraded, and reinstalled without significant material degradation. The theoretical underpinning is that reversibility extends useful life and preserves higher-value material flows compared to downcycling.

**Prefabrication as an enabling modality.** Prefabrication offers controlled manufacturing environments where quality is assured and material substitutions (including CDW-derived materials) can be integrated with predictable outcomes (Minunno et al., 2018). Prefabricated components can be engineered for demountability and standardized connections, thereby simplifying future deconstruction and reuse. However, the literature cautions that prefabrication alone does not guarantee circularity; design intent and material specification remain decisive (Pecur et al., 2014).

**Incorporation of recycled CDW in prefabrication.** Empirical and experimental studies reveal that CDW can serve as feedstock in new prefabricated elements and hybrid composites. Keskisaari et al. (2016) demonstrate that construction and demolition wastes used as mineral fillers in wood-polymer composites can produce functional materials, though mechanical and durability attributes depend heavily on filler cleanliness, particle-size distribution, and processing. Pecur et al. (2014) describe an innovative prefabricated system that utilized recycled CDW elements for both new construction and renovation, indicating feasibility when systems are designed to accommodate material variability.

**Upcycling and superuse.** Superuse and upcycling approaches transform waste into higher-value building applications through creative design, reducing raw material demand while creating architectural and material value (Altamura & Baiani, 2019). The literature emphasizes the need for design tools and methods to systematically identify reuse opportunities, bridging aesthetics and technical performance.

**Deconstruction economics and case evidence.** Deconstruction—manual dismantling to recover components—can yield superior recovery rates compared to demolition, though it often incurs higher upfront labor costs. Lassandro's case study (2003) in Southern Italy provides granular economic and environmental assessments that highlight contexts where deconstruction is both viable and beneficial, particularly when valuable materials (timber, fixtures) are present and secondary markets exist. Forsythe (2011) discusses how demolition decisions, influenced by economic drivers and policy, impact timber waste management; decisions favoring demolition over refurbishment preclude opportunities for material reuse.

**Material morphology and recycled fiber behavior.** The micro- and macromorphology of recycled fibers and wood significantly influences composite properties (Stokke, 1992). Recycled fibers often exhibit morphological degradation that affects bonding with polymer matrices; processing strategies that compensate for altered morphology are necessary to maintain structural performance.

### Lifecycle assessment and methodological sensitivity

**Relevance of LCA simplifications.** Kellenberger and Althaus (2009) argue that LCA results for building components are highly sensitive to methodological simplifications. Simplifications—such as excluding transport distances, ignoring end-of-life scenarios, or using aggregated data—can invert conclusions about environmental superiority. Erlandsson and Borg (2003) similarly emphasize the need for generic, transparent LCA methodologies tailored for buildings, highlighting areas needing development.

**End-of-life assumptions and carbon implications.** End-of-life management substantially affects lifecycle carbon outcomes. Dadoo et al. (2009) analyze carbon implications of end-of-life decisions, demonstrating that reuse and controlled disassembly can yield significant carbon savings when substitution effects are counted. Conversely, improper end-of-life treatments and energy-intensive processing of recycled materials can offset potential gains.

**Phase change materials and embodied implications.** De Gracia et al. (2010) study inclusion of phase change materials in buildings—an intervention that affects operational energy but also introduces embodied impacts. The lesson for circular strategies is that interventions must be assessed holistically across all lifecycle phases.

### Process-level and digital enablers

**BIM and material traceability.** Eastman et al. (2011) underline the transformative potential of Building Information Modeling (BIM) in rendering material attributes, enabling traceability, and supporting lifecycle management. BIM's data-rich outputs can encode provenance, material composition, and connection types—critical information for future deconstruction and reuse. Kapogiannis and Sherratt (2018) further argue that integrated collaborative technologies foster a collaborative culture essential for circular outcomes.

**Collaborative contracting and integrated project delivery.** Relational contracting and integrated project delivery models align stakeholder incentives and promote information sharing, risk distribution, and innovation (Matthews & Howell, 2005; Love et al., 2008). These models reduce adversarial behavior inherent in traditional contracting and encourage joint problem solving that can embed circular ambitions into project planning and execution.

Public procurement as a lever for circularity. Public sector organizations can catalyze circular practices through procurement, especially in mega-projects where project scale affects markets (Klein et al., 2020; Alotaibi et al., 2024). Lingegård et al. (2021) show that integrated contracts in infrastructure can facilitate circular public procurement by specifying lifecycle performance and incentivizing material retention. However, procurement must be designed to value lifecycle benefits rather than short-term cost metrics to meaningfully shift the market.

Socio-organizational drivers, awareness, and barriers

Awareness and practice gaps. Studies indicate variable awareness and inconsistent practice of circular principles among built environment professionals (Amudjie et al., 2023). The gap between conceptual understanding and applied methods is a major barrier to scaling circular approaches.

Barriers catalogued. Kirchherr et al. (2018) categorize barriers to circular economy adoption—including regulatory constraints, lack of standardized metrics, limited financial incentives, and market fragmentation. These barriers frequently intersect: for example, the absence of material standards for recycled CDW undermines procurement confidence, which in turn reduces demand and investment in recycling infrastructure.

Drivers and enablers. Drivers identified include environmental regulation, corporate sustainability commitments, economic incentives for material efficiency, and technological enablers such as BIM. The literature converges on the point that enabling frameworks must be systemic and multi-stakeholder to be effective (Geissdoerfer et al., 2017; Karhu & Linkola, 2019).

Cross-cutting insights

Synergies and trade-offs. Integrating recycled CDW into prefabrication delivers synergies: reduced virgin material demand, potential embodied carbon reductions, and market creation for secondary materials. However, trade-offs include possible durability concerns, costs associated with quality assurance and deconstruction, and the need for harmonized standards to assure performance. Kellenberger and Althaus (2009) caution that lifecycle gains can be sensitive to those trade-offs and methodological choices.

Scalability constraints. Scaling circular approaches faces both supply-side and demand-side constraints. Supply-side issues include heterogeneity of CDW streams and limited processing infrastructure. Demand-side issues include low contractor confidence, procurement practices that prioritize low capital cost, and fragmented value chains. Strategic interventions must therefore address both sides simultaneously.

Synthesis into an integrative framework. The combined evidence suggests a three-pronged intervention strategy: (1) embed circularity at the design and material level through design-for-change, modularity, and recycled-material engineering; (2) employ process and digital enablers—BIM, collaborative platforms, and quality-control protocols—to manage complexity and assure performance; and (3) reform procurement and contracting to align incentives with lifecycle outcomes and support deconstruction and material markets. Each prong mutually reinforces others, implying that piecemeal interventions will have limited effect unless supported by systemic shifts.

## DISCUSSION

The preceding results provide a dense tapestry of evidence and theoretical rationale for a systems-oriented approach to circular construction. This discussion elaborates on theoretical implications, practical tensions, limitations, counter-arguments, and future research directions.

Theoretical implications: reconciling circularity with construction practice. Circular economy literature frames circularity as a system-level redesign that emphasizes material loops, product-service systems, and slowing resource flows (Kirchherr et al., 2017; Geissdoerfer et al., 2017). Translating this paradigm into construction practice requires reconciling the industry's episodic, project-based nature with the continuous flows required by circular systems. Buildings are unique in-site, financing, regulation, and stakeholder involvement; thus circularity must be operationalized with strategies that respect project-based realities—prefabrication is one such strategy because it concentrates interventions into manufacturing processes that can standardize circular attributes (Minunno et al., 2018). However, the theory must also accommodate the social and institutional aspects—procurement, contracts, and markets—that mediate material flows.

Procurement as the critical political economy lever. The literature highlights procurement as a critical mechanism to re-align incentives; without procurement reform, technical innovations are unlikely to scale (Matthews & Howell, 2005; Lingegård et al., 2021). Public procurement can act as a demand anchor for recycled-material prefabrication by specifying lifecycle requirements, mandating material traceability, and offering longer-duration contracts that internalize deconstruction and reuse. However, such procurement must be designed with careful risk allocation to avoid penalizing early adopters. Integrated contracts and relational models provide templates for such allocation by promoting shared objectives and continuous collaboration (Matthews & Howell, 2005; Love et al., 2008).

Lifecycle assessment complexities and their implications. LCA remains central to claims about circular benefits, yet results hinge on methodological choices. Kellenberger and Althaus (2009) present a rigorous critique of simplifications; this has profound implications. For instance, if LCA excludes transport distances for CDW processing, a recycled-material strategy might seem advantageous, but if transport is significant—e.g., long distances between demolition sites and recycling plants—the benefit can erode or reverse. Therefore, practitioners and policymakers must demand transparent, context-specific LCAs that include end-of-life scenarios, substitution effects, and sensitivity ranges. This requirement is both technical and institutional: standard LCA guidelines for building projects must evolve to integrate circularity-specific parameters (Erlandsson & Borg, 2003).

Material performance and quality assurance. Scientific studies (Stokke, 1992; Keskiisaari et al., 2016) show recycled fibers and CDW fillers can be integrated into composite materials with acceptable properties, but performance is contingent on feedstock quality and processing. Manufacturing prefabricated components with recycled inputs requires robust quality assurance systems: sampling protocols, compositional testing, and performance validation across environmental exposures. These activities introduce costs and technical requirements that procurement and market mechanisms must recognize. Otherwise, contractors will substitute uncertified recycled materials or avoid them altogether, undermining circular ambitions.

Economic considerations: deconstruction versus demolition. Deconstruction yields higher material recovery but often at higher upfront labor costs compared to mechanical demolition. Lassandro's (2003) case study demonstrates contexts where deconstruction is economically advantageous—particularly when secondary markets exist and when labor costs or regulations incentivize material recovery. Policy tools (subsidies for deconstruction, differential landfill taxes, or material recovery targets) can shift the calculus. Additionally, circular business models such as product-as-a-service or take-back schemes can internalize the benefits of deconstruction by creating producer responsibility and long-term revenue streams.

Behavioral and organizational barriers. The literature documents awareness and practice gaps among practitioners (Amudjie et al., 2023). Awareness campaigns alone are unlikely to trigger systemic change. Instead, organizational learning, pilot projects, and demonstrator programs combined with procurement conditions create experiential knowledge that reduces perceived risk. Collaborative technologies (BIM, shared platforms) can support this learning by making material information explicit and portable across project phases (Eastman et al., 2011; Kapogiannis & Sherratt, 2018).

Policy coherence and standards. For secondary materials to enter mainstream supply chains, standardization and certification are essential. Standards specifying acceptable material properties, testing methodologies, and labeling for recycled-content prefabricated components would reduce buyer uncertainty. The literature points to fragmentation as a barrier (Kirchherr et al., 2018); coordinated policy efforts that integrate environmental performance targets, procurement guidelines, and standards can create predictable markets.

Counter-arguments and uncertainties

Potential greenwashing and rebound effects. A common critique is that circular strategies can be co-opted as greenwashing if they prioritize appearance over substance or if lifecycle benefits are overstated through selective boundaries. Rigorous, transparent LCAs and third-party verification of recycled-material content and performance are necessary to mitigate this risk (Kellenberger & Althaus, 2009).

Rebound effects—where efficiency gains lower costs and stimulate increased consumption—could undermine material savings. For example, lower embodied carbon through recycled-content materials might reduce perceived urgency for broader systemic changes. Addressing rebound effects requires policy levers and broader sustainability metrics beyond single-product efficiencies.

Heterogeneity of CDW and scalability limitations. CDW streams are heterogeneous, containing mixed materials, contaminants, and variable proportions depending on demolition practices and building typologies. Processing technologies must be adaptable and robust; small-scale processing may be uneconomical. The literature suggests that regionalized approaches with local processing hubs and coordinated procurement can partially address these constraints (Pecur et al., 2014; Keskiisaari et al., 2016).

Future research priorities

Empirical demonstrations at scale. While pilot projects illustrate feasibility, large-scale empirical studies are required to quantify lifecycle benefits across varied contexts, considering transport, processing, and substitution effects. Multi-site trials of prefabricated systems using recycled CDW across climates and regulatory regimes would address knowledge gaps.

Advanced LCA protocols for circular construction. Developing and validating LCA protocols that explicitly account for reversibility, product-service models, and multi-life cycles of components is essential. Research should propose standardized sensitivity analyses to reveal how boundary choices impact conclusions.

Market and procurement experiments. Field experiments—where procurement instruments (e.g., lifecycle-based scoring, material passports, or extended warranties) are deployed and evaluated—would help identify the most effective policy levers.

Materials innovation and processing. Continued research into the morphology and engineering of recycled fibers, admixtures, and hybrid composites will expand the palette of feasible recycled materials for load-bearing and non-load-bearing applications.

Limitations

The analysis is constrained by reliance on a pre-specified reference list. While this limitation ensures fidelity to the user-provided literature, it necessarily excludes broader or more recent studies that might contribute additional nuance—particularly in rapidly evolving areas such as digital material passports, regulatory change post-2024, and novel recycling technologies. Moreover, the methodological approach is interpretive and synthetic rather than empirical; thus findings emphasize cross-case logic and theoretical integration rather than primary data analysis.

Another limitation is geographic variability. Many case studies and policies are context-specific; outcomes in one regulatory or market environment may not translate directly to others. For example, deconstruction economics in Southern Italy (Lassandro, 2003) are influenced by local labor markets and material values that differ from other regions.

Finally, while this article attempts to cite a supporting reference for major claims, the depth of technical detail in areas such as composite processing and LCA computational assumptions is limited to what existing referenced works report; further technical validation would benefit from experimental data.

Future scope

Implementing the proposed integrative framework invites coordinated action across research, industry, and policy domains. Key priorities include:

1. Establishing regional hubs that combine CDW processing with prefabrication facilities to reduce transport burdens, ensure material quality, and create circular supply chains.
2. Developing standardized material passports within BIM ecosystems to encode provenance, material composition, and connection details, facilitating reuse and LCA transparency.
3. Piloting procurement models that internalize lifecycle benefits—e.g., awarding contracts based on whole-life cost and environmental performance, combined with relational contracting.
4. Incentivizing deconstruction through fiscal measures and capacity building to increase recovered material volumes and develop secondary markets.
5. Investing in materials research targeting the durability, fire performance, and structural properties of recycled-content composites for broader application.

Collectively, these steps can convert promising pilots into systemic change, aligning design, manufacturing, and procurement around circular principles.

## CONCLUSION

This article synthesizes a body of work that converges on a clear conclusion: attaining circularity in the built environment requires integrated action across design, materials, digital processes, and procurement. Prefabrication provides a powerful modality for embedding circular principles due to controlled manufacturing, standardization potential, and the ability to engineer disassembly. Recycled CDW can be incorporated into prefabricated systems and composites, but success depends on rigorous quality control, appropriate processing, and context-specific design. LCA remains indispensable for assessing environmental outcomes, yet practitioners must avoid simplifications and ensure transparent, context-sensitive modeling. Procurement and contracting structures are arguably the most powerful levers for systemic change; integrated and relational models enable the alignment of incentives necessary to internalize circular benefits.

The transition to circular construction is not merely a technical challenge but a socio-institutional one: it requires collaborative cultures, standards, and policy frameworks that encourage experimentation and scale successful models. While obstacles persist—heterogeneous CDW streams, methodological complexity in environmental assessment, and procurement inertia—the literature surveyed offers practical strategies and suggests a credible pathway forward. Unlocking this potential demands coordinated demonstration projects, procurement innovation, and rigorous lifecycle analysis to ensure circularity delivers tangible environmental and economic benefits at scale.

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