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Circularity By Design: A Systems Framework For Reuse, Recycling, And Secondary-Resource Integration In The Built Environment

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Abstract: Background: The built environment is responsible for substantial material throughput, waste generation, and lifecycle environmental impacts. Scholarship across materials science, construction management, policy, and industrial ecology emphasizes reuse, recycling, and design-for-disassembly as central strategies for decoupling building-sector growth from resource depletion (Jawahir & Bradley, 2016; Jones & Comfort, 2018). Yet implementation remains fragmented by technical, economic, regulatory, and social barriers (Hart et al., 2019; Hjaltadóttir & Hild, 2021).

Objectives: This article constructs an integrative, publication-ready conceptual and methodological framework—grounded exclusively in the provided literature—that synthesizes material-level interventions (e.g., wood-plastic composites, recycled timber), component- and building-level reuse strategies (e.g., whole-house deconstruction, load-bearing component reuse), procurement and policy levers (e.g., circular procurement), and enabling digital-technological tools (e.g., BIM for demolition planning). It aims to reconcile disparate empirical findings into a coherent research agenda and actionable decision framework for practitioners, policymakers, and researchers.

Methods: A critical integrative review approach was used, combining thematic synthesis, cross-case comparative analysis, and systems-mapping. Source materials included experimental materials research, case studies of deconstruction and reuse, life-cycle and economic feasibility analyses, policy and procurement scholarship, and technological studies on digital tools for demolition and waste estimation (Keskisaari & Kärki, 2018; Bouslamti et al., 2012; Zaman et al., 2018; Cheng & Ma, 2013). Each source was interrogated for contribution to technical feasibility, economic viability, regulatory impediments, stakeholder dynamics, and design implications. Claims are triangulated across multiple sources, and where tensions exist, alternative interpretations are explored.

Results: The synthesis identifies four mutually reinforcing domains necessary for scalable circularity in the built environment: (1) material innovation and substitution pathways (e.g., wood-plastic composites employing industrial wastes); (2) building- and component-level recovery systems (e.g., systematic deconstruction and reuse of load-bearing elements); (3) institutional and market mechanisms (e.g., circular procurement and cost-competitive reuse supply chains); and (4) digital and process enablers (e.g., BIM-based waste estimation and mapping of material flows). Critical bottlenecks identified include uncertain cost attribution for secondary materials, quality and performance variability in reclaimed materials, regulatory ambiguity over reused structural elements, and information asymmetries inhibiting reuse markets (Yeung et al., 2017; Sigrid Nordby, 2019; Serwanja & Sheidaei, 2016).

Conclusions: Transitioning to circular built environments requires coordinated interventions across technical, institutional, and informational axes. Design for Reuse, integrated procurement strategies, and digital traceability constitute a combined pathway to reduce lifecycle impacts while maintaining safety and cost-effectiveness. Research priorities include standardized performance metrics for reclaimed materials, procurement models that internalize circularity benefits, and scalable logistics models for deconstruction and material redistribution. The article closes by proposing a detailed research and policy agenda that operationalizes the integrated framework introduced.

Keywords: Circular economy, reuse, recycled timber, design for disassembly, deconstruction, wood-plastic composites.

Introduction: The acceleration of urbanization and infrastructure development in the twenty-first century has amplified the quantity and complexity of materials flowing through the built environment (Jones & Comfort, 2018; Hossain et al., 2020). Traditional linear patterns—extract, manufacture, build, demolish, discard—have locked construction sectors into a pattern of massive material throughput and persistent waste streams. Recognizing this unsustainable trajectory, academic, industry, and policy communities have converged on circular economy principles that seek to close material loops, extend service life, and transition from ownership of material to stewardship of function (Jawahir & Bradley, 2016; Gupta et al., 2019). In the construction sector, the implications are profound: buildings present an enormous stock of materials that, if systematically recovered and reintegrated, could significantly reduce virgin material demand, embodied carbon, and waste management burdens (Hjaltadóttir & Hild, 2021; Hart et al., 2019).

Despite consensus on the promise of circular approaches, operationalizing circularity in the built environment remains elusive. Empirical research reveals technical feasibility for many reuse and recycling strategies—such as manufacturing wood-plastic composites with industrial wastes (Keskisaari & Kärki, 2018) or repurposing structural steel with life-cycle cost benefits (Yeung et al., 2017)—but also common impediments. These include uncertainties regarding the structural integrity of reclaimed components, fragmented supply chains for reused materials, regulatory frameworks not fully accommodating reused elements, and cultural or organizational resistance within procurement and design practices (Sigrid Nordby, 2019; Bertin et al., 2019). Moreover, the enforcement of material quality and accountability across lifecycle stages requires digital traceability and data infrastructures that are only just emerging (Cheng & Ma, 2013; Kanther, 2025).

The present article addresses a pressing need: an integrated, research-grounded framework that synthesizes evidence across materials research, case-based deconstruction studies, policy and procurement literature, and technology-enabled approaches—using exclusively the provided references. The goal is not merely to recount individual studies but to weave them into a systems-level architecture that reveals leverage points for research and practice. By doing so, the article aims to clarify how technical innovations (e.g., wood-plastic composites), design strategies (e.g., Design for Reuse), procurement reforms (e.g., active procurement for secondary materials), and digital tools (e.g., BIM-based demolition planning) interact to enable or impede circularity in buildings.

The literature supplied spans experimental material science, applied case studies of reuse and deconstruction, economic feasibility studies, procurement and policy analyses, and technological frameworks for demolition planning. These sources provide complementary vantage points: material-level studies show substitution potential and performance characteristics (Keskisaari & Kärki, 2018; Bouslamti et al., 2012), case studies illustrate logistical pathways and social/organizational trade-offs in whole-house reuse (Zaman et al., 2018; Lantz et al.), and policy/procurement literature highlights systemic levers and stakeholder incentives (Gupta et al., 2019; Gyori, 2022). Synthesizing these insights allows us to design a theoretically rich and practically oriented framework that maps technical, economic, institutional, and informational dimensions of circularity, and to propose concrete research and policy agendas for each.

This introduction sets out three central research questions that guide the analysis: (1) What are the technical and material pathways for substituting virgin materials with secondary or recycled materials in building applications? (2) What institutional, economic, and regulatory barriers and enablers shape the adoption of reuse and recycling at component and building scales? (3) How can digital and process innovations (e.g., BIM, procurement frameworks) be combined with design strategies to scale circular practices? The remainder of the article is structured to respond to these questions through a detailed methodology, descriptive results synthesizing the literature, a deep discussion of implications and limitations, and an actionable conclusion with research priorities.

Methodology

The methodological approach adopted in this study is a critical integrative synthesis designed to produce an original conceptual framework grounded in the supplied literature. This method emphasizes careful, transparent interrogation of each source for its empirical claims, theoretical contributions, and contextual limitations, and then builds across sources to generate higher-order insights that no single study could provide alone. Three interrelated techniques were used: thematic synthesis, comparative case analysis, and systems-mapping. Each is explained in turn, with justification for why they are appropriate given the nature of the references.

Thematic synthesis was selected because the literature set includes a heterogeneous mix of empirical methods and disciplinary perspectives—experimental material studies, case papers on deconstruction and reuse, economic feasibility analyses, and policy-oriented scholarship (Keskisaari & Kärki, 2018; Zaman et al., 2018; Yeung et al., 2017; Gupta et al., 2019). Thematic synthesis allows extraction of recurring themes—such as material performance variability, procurement barriers, and digital information needs—and organizes these into analytically useful categories. In practice, each reference was reviewed, and core findings were coded into a set of preliminary themes: material substitution potential, component recovery logistics, cost and life-cycle trade-offs, regulatory and standards issues, procurement dynamics, and information/digital tools. These themes were iteratively refined as cross-references and contradictions surfaced.

Comparative case analysis was applied to specific case-based references that describe real-world interventions—most notably whole-house deconstruction and reuse cases, and feasibility studies of recycled timber and steel reuse (Zaman et al., 2018; Lantz et al.; Yeung et al., 2017). Comparative analysis across cases highlights patterns of success and failure, and elucidates context-sensitive variables such as scale, market demand for reclaimed materials, and availability of skilled labor. This technique is particularly appropriate for building-sector interventions where outcomes depend heavily on local market structures and regulatory contexts (Sigrid Nordby, 2019; Brütting et al., 2019).

Systems-mapping is the integrative phase where the thematic findings and comparative case insights are translated into a coherent conceptual architecture. The mapping delineates the actors, flows, and feedback loops necessary for circularity: material sources (industrial wastes, reclaimed timber), transformation pathways (processing, remanufacture into wood-plastic composites or structural components), distribution and procurement mechanisms (marketplaces, active procurement), technical standards and regulatory gates, and enabling digital/informational systems (BIM-based waste estimation, traceability). This systems perspective allows for the identification of leverage points and bottlenecks across multiple scales—material, component, building, supply chain, and institutional.

Throughout this synthesis, rigorous citation practice is employed: every major claim is supported by one or more references from the provided list. Where the literature reveals disagreement or uncertainty—for example, between optimistic material substitution potential and the practical variability in reclaimed material quality—these tensions are explicitly discussed and synthesized. The methodology is rooted in qualitative synthesis rather than original experimental data collection. Consequently, the “results” reported are analytical constructs derived from the evidence base rather than new empirical measurements. This approach is appropriate given the tasked constraint: to generate an original research article strictly based on the supplied references.

Limitations of the methodological approach are acknowledged and addressed in subsequent sections: the analysis is bounded by the selection of sources provided, which may not represent the full global literature; the absence of primary quantitative datasets constrains the ability to produce novel numerical estimates; and the integration relies on the quality and scope of existing case studies. Nevertheless, by systematically triangulating across diverse reference types and explicitly mapping assumptions and uncertainties, the study produces a robust, publication-ready conceptual framework and a prioritized research agenda.

Results

The integrative analysis produced a multi-layered set of findings organized around four principal domains that together define a workable pathway for circularity in construction: material innovation and substitution; component and building recovery systems; institutional and market mechanisms; and digital and process enablers. Each domain is described below in detail, with extensive elaboration of mechanisms, supporting evidence from the literature, and critical nuances.

Material Innovation and Substitution Pathways

One of the most tangible routes to circularity is through material substitution—replacing virgin inputs with recycled, reclaimed, or industrial-waste-derived materials that meet performance and safety requirements while offering environmental benefits. The literature provides concrete examples and theoretical rationales for such substitutions.

Keskisaari and Kärki (2018) document the utilization of industrial wastes from mining and packaging industries in wood-plastic composites (WPCs). Their study demonstrates that industrial residues can be valorized as fillers or reinforcements within polymer matrices, producing composite materials suitable for a range of non-structural building applications. The technical promise of WPCs produced with secondary materials lies in the ability to tailor mechanical properties (stiffness, impact resistance), moisture resistance, and durability through formulation choices and processing parameters. Such composites can substitute for traditional timber or polymer products in cladding, decking, and non-load-bearing panels, thereby diverting waste streams while reducing demand for virgin timber and virgin polymers.

However, the literature cautions that material substitution requires rigorous characterization and standardization. Bouslamti et al. (2012) emphasize the importance of simulating a representative sample of recycled wood when assessing recycled-wood products; heterogeneity in reclaimed wood—arising from prior use, species mix, moisture history, and contamination—affects mechanical behavior and durability. Therefore, laboratory protocols must reflect real-world variability to ensure performance reliability in building applications. This observation highlights a broader methodological requirement: materials research must move beyond "ideal" recycled feedstocks to account for the statistical distribution of properties that will be encountered in practice.

The substitution pathway also raises questions of lifecycle benefits and trade-offs. Life-cycle perspectives show that recycled materials can yield lower embodied energy and emissions, but these benefits are contingent on processing requirements, transport distances, and the need for remedial treatments (Citherlet & Defaux, 2007; Cole et al., 1996). In particular, when reclaimed materials require intensive remediation or chemical treatment to meet building codes, the net environmental advantage may be reduced. The implication is that substitution strategies should be assessed holistically, considering not only material feedstock but also processing intensity and end-of-life scenarios.

A further consideration is the fit between material application and reclaimed-material properties. Non-structural applications—where mechanical performance requirements are less demanding—are natural first adopters of recycled materials (Keskisaari & Kärki, 2018). Structural reuse requires stricter verification; yet case studies show the feasibility of reusing structural steel and timber when appropriate testing and certification procedures are in place (Yeung et al., 2017; Brütting et al., 2019). The technical path to broader substitution thus involves a staged approach: prioritize low-risk applications for recycled-content materials while developing robust certification and testing regimes for higher-risk structural uses.

Component and Building Recovery Systems

The literature highlights the operational modalities for recovering usable materials and components from buildings. Recovery ranges from targeted component salvage during planned renovation to systematic whole-house deconstruction that seeks to maximize material recovery.

Zaman et al. (2018) present a case study of a "whole house reuse" project in Christchurch, New Zealand, demonstrating the feasibility and logistical considerations of deconstructing a residential house for material harvesting. Their systematic deconstruction approach emphasizes careful sequencing, manual dismantling of valuable elements (e.g., doors, windows, joinery), and rigorous cataloguing of recovered items. The case underscores several operational insights: first, deconstruction is labor-intensive and requires skilled crews trained in salvage techniques; second, pre-demolition assessment and planning are essential to identify reclaimable components and to anticipate hazardous materials; and third, markets for reclaimed components must be cultivated to absorb recovered items at scale.

Lantz and Falk (1997) explore recycling timber from military industrial buildings, pointing to the potential for large-scale timber recovery where building fabric is homogeneous and well-documented. Their analysis shows that institutional projects—where a single organization manages multiple buildings—can capture economies of scale that make salvage more cost-effective. The military context illustrates how centralized asset management and planned deconstruction can overcome some of the market fragmentation that hinders salvage in more dispersed residential contexts.

Brütting et al. (2019) analyze the reuse of load-bearing components, which is a critical frontier for circular construction. Load-bearing elements—beams, columns, trusses—represent significant material mass and embodied carbon, so their reuse yields outsized benefits if structural safety can be ensured. The authors discuss design modifications to facilitate disassembly, such as reversible connections and modularity, thereby enabling future recovery. They also note regulatory barriers: existing building codes and certification processes often lack clear pathways to accept reused structural elements, creating uncertainty for engineers and owners.

Comparative analyses across these studies emphasize the interplay between technical feasibility and market dynamics. Salvage operations must be matched with demand-side mechanisms, whether through direct reuse markets, refurbishment and resale channels, or remanufacturing into secondary products (e.g., WPCs). The lack of integrated logistics—collection, sorting, certification, storage—creates friction that limits recovery rates. Moreover, the labor-intensity of deconstruction suggests that cost-effective recovery may require policy support (e.g., subsidies, tax incentives) or procurement strategies that internalize the value of recovered materials (Ankur, 2019; Gyori, 2022).

Institutional and Market Mechanisms

Institutional dynamics—procurement practices, policy frameworks, and market structures—significantly influence the feasibility of circular practices. Several references offer direct insight into these mechanisms.

Ankur (2019) develops an assessment framework for accelerating circularity in the built environment via “active procurement”—an approach that aggregates demand for secondary materials early in the design phase. The principle is straightforward: designers and procurers explicitly aim to use secondary materials and embed this objective into specifications, tendering criteria, and supplier evaluation. Active procurement can create guaranteed demand for reclaimed materials, thereby reducing market uncertainty and encouraging suppliers to invest in processing and certification infrastructure. Ankur’s thesis situates procurement as a strategic lever to align design intent with circular outcomes.

Gupta et al. (2019) explore the interplay between circular economy and big data analytics from a stakeholder perspective. Their work suggests that data-driven insights—on material flows, lifecycle impacts, and supplier capabilities—can inform procurement decisions and lifecycle-based accountability. Big data analytics, when integrated into procurement systems, can identify opportunities for reuse, optimize logistics, and quantify the environmental benefits of secondary-material choices. However, data infrastructures and stakeholder collaboration are preconditions; without them, procurement reforms remain aspirational.

Gyori (2022) interrogates public procurement as a tool to foster social equity and justice alongside circular outcomes. The author critically reflects on circular procurement concepts that emphasize environmental gains but may overlook distributive impacts—such as who benefits from reclaimed-material markets and whether procurement processes promote small-scale or marginalized suppliers. This cautionary perspective indicates that procurement must be designed to achieve multiple societal objectives, not only material circularity.

Hjaltadóttir and Hild (2021) analyze European policy and local practices regarding circular economy in construction, showing that policy frameworks can incentivize or constrain reuse depending on clarity, enforcement, and local adaptation. Their work indicates that harmonized standards and supportive regulation (e.g., allowing reuse within building codes under defined conditions) can reduce uncertainty and catalyze investments in reuse infrastructure.

Economic feasibility analyses further illuminate institutional barriers. Serwanja and Sheidaei (2016) evaluate recycling and reuse from demolition, considering cost feasibility and environmental impacts. Their analysis finds that while environmental benefits are often evident, cost competitiveness depends on factors such as labor costs, transport distances, market demand for secondary materials, and regulatory compliance costs. These variables create spatial and contextual heterogeneity: what is feasible in one jurisdiction or project may be uncompetitive in another.

Taken together, the literature suggests that institutional mechanisms are not purely policy levers or procurement tools in isolation; rather, they must be orchestrated to reduce market friction, internalize externalities (e.g., environmental benefits), and align incentives across supply and demand. Active procurement, data-driven decision support, inclusive procurement designs, and supportive regulation constitute a portfolio of institutional measures that can collectively unlock higher rates of reuse and recycling.

Digital and Process Enablers

Information and digital tools are recurring themes in the literature as critical enablers for circularity. BIM-based systems and digital traceability are highlighted as means to improve demolition planning, estimate recoverable materials, and provide provenance for reclaimed components.

Cheng and Ma (2013) present a BIM-based system for demolition and renovation waste estimation and planning. Their work demonstrates how digital models of buildings—when enriched with material metadata—enable more accurate forecasting of recoverable material quantities and types. BIM can facilitate pre-demolition audits, identify components suitable for salvage, and generate material inventories that inform logistics and market matching. Cheng, Won, and Das (2015) extend this line of thought by exploring BIM for construction and demolition waste management, thereby underscoring the potential for digital tools to reduce uncertainty and logistical inefficiencies.

Kanther (2025) provides a contemporary thesis on circular frameworks in the design and planning phase of construction, reflecting the growing emphasis on integrating circularity early in project lifecycles. Early-stage digital modeling and procurement specifications that prioritize secondary materials can bridge design intent and actual construction practice. When BIM models are combined with material databases, lifecycle assessment modules, and supplier registries, designers and procurers can quantify trade-offs and select circular options with greater confidence.

Gupta et al. (2019) argue that big data analytics—applied to material flows, supplier performance, and lifecycle impacts—can inform stakeholder decisions and optimize closed-loop material flows. Data-driven insights enable scenario analysis, risk assessment, and performance verification, which are essential when dealing with reclaimed materials whose properties may vary. Digital traceability—linking a reclaimed component to its provenance, testing history, and remanufacturing steps—further reduces information asymmetry and can facilitate regulatory acceptance.

However, digital enablers also face practical barriers: data fragmentation, lack of interoperability between systems, and the extra overhead of populating digital models with accurate material metadata. Moreover, small-scale suppliers in reclaimed-material markets may lack the resources to participate in sophisticated digital platforms, posing an inclusion challenge (Gyori, 2022). Thus, digital tools must be designed to be interoperable, user-friendly, and accessible to a diverse range of market actors.

Cross-Domain Synthesis: Feedbacks, Bottlenecks, and Leverage Points

The four domains described above are interdependent and generate feedback loops that either amplify circularity or reinforce linearity. Several cross-domain insights emerge:

1. Quality–Market Feedback Loop: The perceived and actual quality of reclaimed materials influences market demand. Low demand depresses prices and reduces investments in processing, which in turn leads to poorer sorting and lower-quality secondary materials—perpetuating a low-quality, low-demand equilibrium (Bouslamti et al., 2012; Serwanja & Sheidaei, 2016). Breaking this cycle requires interventions that guarantee quality (certification, testing) and create demand (procurement commitments).

2. Design–Recovery Feedback Loop: Design choices affect recoverability. Buildings designed with reversible connections and component standardization facilitate salvage and remanufacture (Bertin et al., 2019). Conversely, conventional monolithic construction increases demolition complexity and contamination, reducing recoverability. Therefore, embedding Design for Reuse principles early in design is a high-leverage intervention.

3. Policy–Market Enabler: Clear regulatory frameworks that accept reused components under defined testing and certification pathways reduce uncertainty for engineers and insurers, thereby enabling reuse, particularly of load-bearing elements (Brütting et al., 2019; Hjaltadóttir & Hild, 2021). Policy signals can catalyze investment in processing and digital traceability.

4. Digital–Procurement Synergy: Digital tools (BIM, data analytics) combined with active procurement create the informational backbone necessary to match recovered supply with demand. Procurement that specifies secondary materials can provide demand certainty, while digital systems ensure that procurement decisions are evidence-based (Cheng & Ma, 2013; Ankur, 2019; Gupta et al., 2019).

5. Economics of Scale: Large projects or institutional asset owners (e.g., military, public agencies) can realize economies of scale for salvage and reuse (Lantz et al.; Yeung et al., 2017). Aggregation of demand—through procurement consortia or centralized marketplaces—can create viable business models for reclamation and remanufacturing.

6. Social and Equity Considerations: Gyori (2022)

warns that procurement reforms must attend to social equity to avoid reinforcing existing inequalities. For example, procurement that privileges large suppliers or tightly specified digital compliance may disadvantage smaller salvage operators. Inclusive procurement design is therefore both an ethical and practical requirement for robust circular markets.

Overall, the results establish that technically feasible material substitutions and operational recovery pathways exist, but their scalable deployment is contingent on institutional coordination, market development, and digital infrastructure. The synthesis also identifies critical research gaps: standardized performance metrics for reclaimed materials, cost-benefit frameworks that internalize environmental and social co-benefits, and logistics solutions for collection and redistribution.

Discussion

The preceding results provide a foundation for deeper interpretation of what is required to transition the built environment toward circularity. This discussion elaborates theoretical implications, addresses tensions and limitations observed in the literature, and proposes a prioritized research and policy agenda.

Theoretical Implications: From Linear to Circular Systems Thinking

A central theoretical implication is the necessity of shifting from component-focused interventions to systems-level thinking. Much existing research—particularly materials studies—produces valuable insights into specific substitution opportunities (e.g., WPCs using industrial wastes), but absent systemic integration these innovations risk remaining niche. A systems perspective emphasizes interdependencies among material properties, design choices, procurement processes, market structures, and information flows (Jawahir & Bradley, 2016; Gupta et al., 2019). This reorientation has three consequences:

First, success metrics for circular interventions must extend beyond single-issue outcomes (e.g., reduction in virgin material use) to encompass systemic indicators such as loop closure rates, quality retention across cycles, and social distributional outcomes (Gyori, 2022). Life-cycle assessments must be integrated with economic and social analyses to capture trade-offs and co-benefits.

Second, interventions should be designed to operate across multiple scales—material, component, building, and regional market networks. For example, a policy intervention that supports salvage at the municipal level should be coordinated with regional processing facilities and procurement consortia to ensure demand absorption.

Third, the systems lens reveals the importance of feedback mechanisms. Policies and procurement strategies that create stable demand can stimulate supply-side investments in processing and certification, which in turn improve the quality and reliability of secondary materials—thereby reinforcing demand. Conversely, neglecting feedbacks risks entrenching a low-demand equilibrium.

Technical and Practical Tensions

Several tensions emerge when translating theoretical promise into practice, which the literature identifies and helps to navigate.

Quality Assurance vs. Cost: Reclaimed materials often require testing, grading, and sometimes remediation to meet building standards. These processes add cost, reducing price competitiveness with virgin materials (Serwanja & Sheidaei, 2016). The literature suggests two partial remedies: (1) targeted application in non-critical uses where performance margins are wide (Keskisaari & Kärki, 2018), and (2) institutional mechanisms (procurement, subsidies) that internalize environmental benefits or account for avoided waste management costs (Ankur, 2019; Gyori, 2022).

Regulatory Ambiguity vs. Safety Assurance: Reused structural elements present safety concerns requiring clear regulatory pathways. Brütting et al. (2019) and Yeung et al. (2017) emphasize that regulatory frameworks must specify testing protocols, allowable reuse conditions, and certification procedures to give engineers and insurers confidence. The tension arises because regulators are risk-averse, and establishing new protocols can be slow. Pilot programs and phased regulatory acceptance for specific components may be pragmatic steps.

Digital Promises vs. Practical Adoption: BIM and big data hold promise for material tracing and waste estimation, yet uptake is uneven and often concentrated in larger firms with digital capacity. To avoid digital divides, platforms must be designed for low-cost participation and interoperability (Cheng & Ma, 2013; Gupta et al., 2019). Public or consortium-led digital registries could provide shared infrastructure.

Market Structure and Power Dynamics

An important normative dimension is the distribution of benefits and burdens in circular transitions. Gyori (2022) raises concerns about social equity: procurement and digital requirements could favor large incumbent firms, marginalize small-scale salvage operators, and concentrate value capture. To ensure broad-based benefits, policy design should incorporate inclusive procurement criteria, capacity-building programs for small enterprises, and mechanisms to ensure fair pricing and market access for reclaimed materials.

Institutional actors such as municipal governments, large public owners, and industry associations have critical roles in enabling inclusive transitions. These actors can aggregate demand, provide financing for processing infrastructure, and offer training programs. The military case discussed by Lantz and Falk (1997) illustrates how centralized ownership can facilitate salvage; analogous public-sector leadership in civilian contexts could play a catalytic role.

Research Priorities and Methodological Innovations

The synthesis identifies several high-priority research questions and methodological needs:

1. Standardized Performance Metrics for Reclaimed Materials: There is a pressing need to develop agreed-upon testing protocols and grading systems for reclaimed timber, steel, and composite materials. Such standards would reduce information asymmetry and facilitate market trust (Bouslamti et al., 2012; Brütting et al., 2019).

2. Integrated Cost-Benefit Frameworks: Research should refine economic models that incorporate not only direct costs but also avoided waste management costs, embodied carbon savings, and social co-benefits. Spatial variability in labor and transport costs should be explicitly modeled to identify contexts where reuse is economically viable (Serwanja & Sheidaei, 2016).

3. Procurement Design Experiments: Empirical studies—ideally randomized or quasi-experimental when possible—should test different procurement strategies (active procurement, set-asides for reclaimed materials, multi-criteria tendering) to assess their effectiveness in creating stable demand (Ankur, 2019; Gyori, 2022).

4. Logistics and Reverse Supply Chain Modeling: Quantitative modeling of collection, sorting, processing, and redistribution networks is needed to identify cost-minimizing configurations and to evaluate the role of aggregation points and regional processing facilities.

5. Digital Traceability Pilots: Implement and evaluate interoperable traceability systems (BIM-integrated material passports, registries) across project lifecycles to examine their impact on market transparency and reuse rates (Cheng & Ma, 2013; Gupta et al., 2019).

6. Social Impact Assessments: Research must assess who benefits from reuse markets, how job creation and skill development are distributed, and whether inclusive procurement designs mitigate disparities (Gyori, 2022).

Methodologically, mixed-methods designs combining laboratory testing, field pilots, economic modeling, and policy analysis will be essential. Interdisciplinary teams can bridge material science, construction management, economics, and public policy to produce robust, actionable insights.

Limitations of the Current Evidence Base

Several limitations within the literature constrain definitive conclusions. Many materials studies are laboratory-based with controlled feedstocks, which may not represent the heterogeneity seen in field-recovered materials (Bouslamti et al., 2012). Case studies of deconstruction often focus on single projects or contexts with unique enabling conditions (Zaman et al., 2018; Lantz et al.). Meanwhile, economic feasibility studies sometimes exclude broader societal benefits or fail to model long-term dynamics of market maturation (Serwanja & Sheidaei, 2016). The digital literature emphasizes potential but lacks extensive field evaluations that demonstrate large-scale impacts on reuse rates (Cheng & Ma, 2013; Gupta et al., 2019). These limitations point to the need for more comparative, longitudinal, and multi-scalar research to build generalizable knowledge.

Policy Implications and Practical Recommendations

Drawing on the synthesis, several practical recommendations emerge for policymakers, procurers, designers, and industry actors:

- Standardize testing and certification pathways for reclaimed structural components to reduce uncertainty and facilitate regulatory acceptance (Brütting et al., 2019; Yeung et al., 2017).
- Adopt active procurement policies that embed secondary-material targets in early-stage design and tender specifications, leveraging public-sector demand to catalyze markets (Ankur, 2019).
- Invest in regional processing infrastructure to achieve economies of scale in sorting, grading, and remanufacturing reclaimed materials (Lantz et al.; Serwanja & Sheidaei, 2016).
- Integrate digital traceability and BIM-based planning into demolition and renovation workflows to forecast recoverable materials and document provenance (Cheng & Ma, 2013).
- Design inclusive procurement mechanisms that lower participation barriers for small-scale salvage enterprises, align social equity goals with circular objectives, and provide capacity-building support (Gyori, 2022).
- Support labor training programs for

deconstruction and remanufacturing to ensure skilled labor supply and safe salvage practices (Zaman et al., 2018).

These recommendations reflect a portfolio approach: no single intervention suffices; coordinated policy, market, and technological measures are required.

Conclusion

This article has synthesized a diverse but thematically coherent body of literature to propose an integrated framework for advancing circularity in the built environment. The analysis, grounded in experimental materials research, case studies of deconstruction and reuse, economic feasibility assessments, procurement theory, and digital-tool development, identifies four interdependent domains—material innovation, recovery systems, institutional mechanisms, and digital enablers—that together constitute the architecture of circularity.

Key conclusions are as follows. First, material substitution pathways—such as wood-plastic composites using industrial wastes—offer viable non-structural applications and reduce virgin resource demand when paired with adequate quality controls (Keskisaari & Kärki, 2018; Bouslamti et al., 2012). Second, building- and component-level recovery systems demonstrate feasibility but are constrained by labor intensity, market fragmentation, and regulatory uncertainty; aggregation and institutional leadership can mitigate these constraints (Zaman et al., 2018; Lantz et al.; Yeung et al., 2017). Third, institutional levers—especially active procurement and supportive regulation—are critical to creating demand and reducing market risk. Procurement that internalizes circular objectives and supports inclusive market participation is a powerful accelerator (Ankur, 2019; Gyori, 2022). Fourth, digital and data-driven tools (BIM, big data analytics, material passports) are necessary to reduce information asymmetry, improve planning, and enable traceability, but practical adoption requires attention to interoperability and equitable access (Cheng & Ma, 2013; Gupta et al., 2019).

The article closes with a prioritized research agenda: develop standardized testing frameworks for reclaimed materials; design and test procurement interventions that create stable demand; model reverse logistics for regional processing; pilot digital traceability systems; and assess social equity outcomes. Achieving circularity in the built environment is not a purely technical challenge; it is a socio-technical transformation requiring coordinated policy, market design, technical standards, and cultural change. The literature provides promising pathways, and the integrated framework advanced here offers a roadmap to guide future empirical work, policy experimentation, and industry action.

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