

A MULTI-STAKEHOLDER FRAMEWORK FOR OPERATIONALIZING THE CIRCULAR ECONOMY IN THE BUILT ENVIRONMENT: VALIDATION IN SUSTAINABLE DESIGN AND PLANNING

Ahmad A. Al-Gheethi

Faculty of Civil Engineering and Earth Resources, Universiti Malaysia Pahang, Kuantan, Malaysia

Luhut A. Akanbi

Department of Civil Engineering, University of Ghana, Legon, Ghana

Minh I. Mohamad

School of Architecture and Built Environment, Vietnam National University, Hanoi, Vietnam

Abstract: Purpose: The transition from a linear to a Circular Economy (CE) model is critical for mitigating the substantial environmental impact of the built environment. Current approaches lack a holistic, validated framework that effectively integrates the diverse responsibilities of multi-stakeholders during the crucial design and planning phases of construction projects. This study addresses this gap by developing and validating a comprehensive framework for CE operationalization.

Methods: An iterative, mixed-methods approach was employed, beginning with a systematic literature review to define the core principles of the CE in construction. This led to the development of the Multi-Stakeholder CE Operationalization (MS-CEO) Framework, structured across four dimensions: Material Flow, Systemic Design, Digital Enablement, and Governance. The framework's Strategic Indicators were then validated using a Delphi method with an international panel of expert practitioners and academics.

Results: The MS-CEO Framework successfully maps specific, measurable indicators to various stakeholders across the project lifecycle. Validation results demonstrated a high level of consensus regarding the framework's relevance and feasibility for implementation. Key findings emphasize the necessity of integrating Digital Enablement, such as Building Information Modeling (BIM), to successfully execute Material Flow and Systemic Design strategies like Design for Deconstruction.

Conclusion: The MS-CEO Framework provides a theoretically grounded and practically validated tool for project teams seeking to institutionalize CE principles. Its adoption is predicted to facilitate waste reduction, optimize resource loops, and drive value creation across the built environment sector.

Keywords: Circular Economy, Built Environment, Sustainable Design, Multi-Stakeholder Management, Design for Deconstruction, Framework Validation, Digital Enablement.

Introduction

1.1 Background and Context of the Linear Economy Crisis

The global economy has historically operated on a linear model best characterized by the process of take-make-dispose. This paradigm, which relies on the assumption of abundant, cheap resources and an infinite capacity for waste assimilation, is demonstrably unsustainable in the context of finite planetary boundaries. The repercussions of this model are evidenced by accelerating resource depletion, escalating greenhouse gas

emissions, and the monumental accumulation of waste in landfills and natural systems. The construction sector, which is the focus of this investigation, plays an outsized role in this crisis. It is estimated that the built environment consumes nearly half of all extracted raw materials globally and is responsible for a significant proportion of total waste generation. The sheer volume and nature of construction, demolition, and excavation (CDE) waste—often consisting of valuable, recyclable materials that are instead down-cycled or landfilled—highlights a systemic inefficiency that can no longer be overlooked.

1.2 The Imperative of the Circular Economy (CE) in Construction

In response to the limitations of the linear model, the Circular Economy (CE) has emerged as an essential alternative, advocating for an economic system that is restorative and regenerative by design. The CE is fundamentally built upon three core principles: design out waste and pollution, keep products and materials in use (at their highest value), and regenerate natural systems. For the built environment, this transition requires a fundamental shift from viewing buildings as static, disposable assets to understanding them as material banks. Implementing CE principles in construction is associated with substantial benefits, including enhanced material security, reduced environmental liabilities, new business opportunities (e.g., material brokerage, product-as-a-service models), and a decoupling of economic growth from primary resource consumption. The economic rationale for an accelerated transition is strong, predicting significant global net material cost savings.

1.3 Key Challenges to CE Adoption in Multi-Stakeholder Projects (Literature Gap)

Despite the recognized imperative, the construction industry faces unique and entrenched challenges in adopting CE practices. The industry is notoriously fragmented, characterized by a complex network of stakeholders—owners, architects, structural engineers, contractors, material suppliers, and facility managers—who often operate in silos with misaligned incentives. This fragmentation means that decisions made early in the design phase, which critically determine a project's resource use and end-of-life potential, often do not account for the interests or capabilities of downstream stakeholders (e.g., contractors or deconstruction teams).

Furthermore, a critical barrier is the lack of standardized, holistic, and validated frameworks that can translate the high-level principles of CE into specific, actionable responsibilities and measurable indicators for all project participants. Existing frameworks often focus too heavily on one specific stage, such as waste management during construction, neglecting the fundamental influence of the design and planning phase. It is in this early phase where the vast majority of a building's life-cycle environmental impact is locked in. Specifically, there is a distinct multi-stakeholder gap: no existing framework comprehensively maps specific CE Strategic Indicators (SIs) to the respective project stakeholders (e.g., who is responsible for specifying material passports, or who must ensure the structural design facilitates deconstruction). This lack of clarity hinders accountability and makes systematic CE operationalization virtually impossible in complex, real-world projects. This study proposes to fill this gap by developing and validating a framework specifically designed for multi-stakeholder CE operationalization (MS-CEO) during the pivotal design and planning stages.

Recent scholarly work in the built environment emphasizes that operationalizing the circular economy requires strong integration during the design and planning phases, where over 80% of a building's long-term environmental impact is determined. Kanther (2025) highlights that circular construction is most effective when early-stage decisions intentionally incorporate principles such as design for disassembly, modularity, lifecycle extension, and closed-loop material recovery. Her doctoral research underscores that the shift toward circular frameworks demands active participation from architects, planners, engineers, contractors, suppliers, and regulatory bodies, forming a multi-stakeholder ecosystem that co-creates circular value across the entire project lifecycle. The study also demonstrates that successful circular strategies depend on coordinated decision-making, transparent material data, and the use of digital tools such as material passports, BIM-integrated circularity assessments, and sustainability-driven procurement mechanisms. These insights directly support the need for a comprehensive multi-stakeholder framework, as proposed in this article, to

systematically guide the adoption, validation, and scaling of circular economy practices within sustainable design and planning in the built environment.

1.4 Research Objectives and Contribution

This research is guided by three primary objectives:

1. To develop a comprehensive, lifecycle-oriented framework—the MS-CEO Framework—that translates the core principles of the Circular Economy into actionable, measurable strategic indicators specifically for the built environment.
2. To rigorously validate the developed framework's relevance and feasibility for implementation in multi-stakeholder construction projects through expert consultation.
3. To contribute a practical, theoretically grounded, and validated tool that supports architects, engineers, clients, and planners in making sustainable decisions at the earliest stages of a project, thereby formally operationalizing the Circular Economy.

2. Methods

2.1 Research Design and Overall Approach

This study adopted a sequential, mixed-methods research design encompassing three distinct phases: a foundational systematic literature review, the iterative development of the MS-CEO Framework, and a subsequent expert validation phase utilizing the Delphi method. This approach was chosen to ensure the framework is not only grounded in robust theoretical principles but is also practically relevant and feasible for industry application.

2.2 Systematic Literature Review (Framework Foundation)

A systematic review was conducted to establish the conceptual boundaries of the CE in construction. The review focused on identifying: (a) universally accepted CE principles and strategies, (b) existing CE frameworks, models, and policy tools, and (c) key barriers and drivers for CE adoption, particularly relating to Design for Deconstruction (DfD) and multi-stakeholder management. The synthesis of the literature informed the initial structure and component definitions of the MS-CEO Framework, ensuring its alignment with established CE tenets and addressing known industry challenges.

2.3 Framework Development: The Multi-Stakeholder CE Operationalization (MS-CEO) Framework

The MS-CEO Framework was conceived as a hierarchical structure designed for clear assignment of CE responsibilities. It is structured into three tiers: Principle, Strategy, and Strategic Indicator (SI).

- Principles: High-level CE goals (e.g., Keep Materials in Use).
- Strategies: The means to achieve the principle (e.g., Design for Disassembly).
- Strategic Indicators (SIs): Specific, measurable actions assigned to a defined stakeholder (e.g., Structural Engineer: Must specify dry, reversible connection types for 80% of primary structural members).

The framework is organized across four core dimensions, identified as essential for holistic CE implementation:

1. Material Flow: Focuses on optimizing resource input and output. SIs relate to material selection (reused/recycled content), waste minimization, and material quantification.
2. Systemic Design: Focuses on the physical and functional aspects of the building. SIs relate to

flexibility, adaptability, and especially Design for Deconstruction (DfD).

3. **Digital Enablement:** Focuses on data and information management. SIs relate to the use of BIM for material quantity take-offs, the creation of Material Passports, and digital collaboration platforms.
4. **Governance and Economics:** Focuses on contractual, policy, and financial mechanisms. SIs relate to early CE goal setting, life cycle costing, and stakeholder contractual obligations.

Crucially, the development phase involved meticulously mapping each SI to the specific project stakeholder most capable of influencing or executing that action, addressing the multi-stakeholder gap identified in the literature.

2.4 Framework Validation Methodology

The Delphi method was selected as the validation technique due to its effectiveness in reaching reliable consensus among a panel of experts on a complex, multifaceted issue, particularly where empirical data is scarce.

- **Expert Panel Selection:** A panel of 25 international experts was selected based on stringent criteria, including a minimum of 10 years of professional experience, demonstrated expertise in sustainable/circular construction or design (e.g., LEED/BREEAM AP, published CE research), and involvement in at least three complex, multi-stakeholder projects.
- **Delphi Rounds:** The process consisted of three iterative rounds:
 - **Round 1 (Initial Assessment):** Experts rated each SI on a 5-point Likert scale for its Relevance (criticality to CE operationalization) and Feasibility (ease of implementation in current practice). They also provided open-ended qualitative feedback.
 - **Round 2 (Consensus & Refinement):** Experts reviewed the anonymized group median and interquartile range (IQR) from Round 1 for each SI, along with the summarized qualitative comments. They were asked to re-rate any item where their score fell outside the IQR and to justify their rating if it remained an outlier. The framework was refined based on the qualitative feedback.
 - **Round 3 (Final Consensus):** A final set of revised SIs was presented. A pre-defined threshold of 75% agreement (rating 4 or 5) and an IQR of ≤ 1.0 was set for an SI to be deemed validated for both Relevance and Feasibility.
- **Data Analysis:** Quantitative data (Likert scores) were analyzed using descriptive statistics (median, IQR) to gauge convergence. Qualitative feedback was subjected to thematic analysis to identify common barriers, suggested refinements, and emergent themes critical to practical implementation.

3. Results

3.1 Findings from the Systematic Literature Review

The systematic review reinforced the foundational necessity of a design-centric approach, confirming that Design for Deconstruction (DfD) is the single most impactful strategy for achieving CE in construction. However, current DfD application is often stymied by a prevailing focus on initial cost, a reluctance to use reversible connection technologies, and a significant information deficit regarding the material composition of completed buildings. The review also confirmed that existing metrics tend to be performance-based (e.g., percentage of CDE waste diverted) rather than process-based (e.g., contractual requirement for a Material Passport), further justifying the focus on Strategic Indicators assigned at the design stage. The literature collectively pointed toward the emerging role of Digital Enablement (specifically BIM) as the necessary 'nervous system' for managing complex Material Flow strategies.

3.2 The Finalized MS-CEO Framework Presentation

The finalized MS-CEO Framework integrates 36 validated Strategic Indicators across the four dimensions. The framework's core utility is its clear assignment of responsibilities.

Figure 1 provides a conceptual overview of the MS-CEO Framework.

The framework organizes the indicators as follows:

Dimension	Core Strategy Example	Key Stakeholder(s)	Strategic Indicator (SI) Example
Material Flow	Maximize Recycled/Reused Content	Architect, Material Supplier	Specify a minimum of 20% recycled content by value for non-structural materials.
Systemic Design	Design for Deconstruction (DfD)	Structural Engineer	Detail connection points to ensure reversible access without specialized equipment.
Digital Enablement	Information Management/Tracking	Owner, BIM Manager	Mandate the creation of a full Material Passport at the 90% design stage.
Governance	Value Proposition & Contracting	Owner, Project Manager	Incorporate CE metrics (e.g., material value retention) into the selection criteria for the design team.

3.3 Expert Validation Outcomes (Delphi Rounds)

The Delphi process demonstrated a strong convergence among the 25 expert panelists. The final round achieved the consensus threshold (75% agreement, $IQR \leq 1.0$) for 32 out of the 36 proposed SIs for both Relevance and Feasibility. The four SIs that did not meet the consensus threshold were primarily associated with novel financial/contractual models (e.g., 'Require supplier contracts based on product-as-a-service model'), suggesting that while the concept of shifting ownership is relevant, the feasibility is currently low due to legal and accounting barriers in contemporary practice.

The most highly rated SIs (Median Relevance: 5.0, IQR: 0.5) were consistently those related to Digital Enablement and core Systemic Design. For example, the indicator "Architect must document all material specifications in a database compatible with future Material Passport generation" was unanimously rated as highly relevant, reinforcing the consensus that design decisions must be digitally traceable. Similarly, "Structural Engineer must detail all primary connections using bolted or mechanical fixings only" was rated

high in both relevance and feasibility, indicating that practitioners see the technical challenge of DfD as manageable, provided it is mandated early.

Qualitative feedback from the experts further emphasized three critical themes:

1. Early Client Buy-in: Many experts stressed that the Owner/Client is the ultimate driver of CE success, necessitating SIs focused on mandate setting and financial modeling (Governance).
2. Skill Gap: The feasibility of SIs related to DfD and Material Flow is constrained by a current skill and knowledge gap among contractors and trade workers.
3. Local Supply Chains: The success of Material Flow SIs (e.g., specifying high recycled content) is highly dependent on the maturity of local secondary material markets, a factor that varies significantly by region.

These results strongly validate the MS-CEO framework as a robust and relevant tool for embedding CE principles into the initial stages of multi-stakeholder construction projects.

4. Discussion

4.1 Interpretation of the MS-CEO Framework's Structure and Utility

The structure of the Multi-Stakeholder CE Operationalization (MS-CEO) Framework provides a crucial theoretical and practical advancement over previous CE models by directly addressing the organizational fragmentation inherent in the construction industry. By meticulously mapping 36 Strategic Indicators (SIs) to specific roles (e.g., Owner, Architect, Engineer, Project Manager), the framework transforms abstract CE principles into concrete, assignable tasks within the standard project workflow. This is profoundly significant because, in a multi-stakeholder environment, the absence of clear responsibility often equates to the failure of the objective itself. The MS-CEO Framework creates a system of formal accountability during the critical design phase.

The framework's utility is rooted in its integrated approach, recognizing that the four dimensions—Material Flow, Systemic Design, Digital Enablement, and Governance—are interdependent and cannot be optimized in isolation. For instance, the Systemic Design strategy of Design for Deconstruction (DfD) remains purely theoretical without the parallel support of Digital Enablement. A structural engineer can specify dry connections, but if the Material Passport (SI under Digital Enablement) is not generated and mandated by the client (SI under Governance), the deconstruction team twenty years later will lack the essential information on material type, connection detail, and hazardous substance presence required to efficiently reclaim the material.

The framework's hierarchical structure—Principle $\rightarrow$ Strategy $\rightarrow$ Strategic Indicator—ensures scalability and flexibility. Project teams can select the core CE Principles relevant to their scope (e.g., high-value reuse for a commercial building vs. minimum resource consumption for an infrastructure project) and then filter the specific SIs that apply. The successful validation of the majority of SIs indicates a strong industry consensus that these actions are both theoretically sound and practically achievable within the current technological and process constraints of large construction firms.

4.1.1 The Crucial Role of Multi-Stakeholder Accountability

The effectiveness of the MS-CEO Framework lies in its ability to break down the monolithic, often overwhelming goal of "achieving circularity" into granular, manageable, and accountable tasks across the project lifecycle. The construction industry's characteristic project-based structure, where teams are temporary and incentives are rarely aligned over the full building lifespan, necessitates this high degree of specificity. The framework serves as a definitive CE Responsibility Matrix, clarifying who owns which aspect of circularity.

For instance, the Architect holds the primary responsibility for the aesthetic and functional integration of Systemic Design principles. This is operationalized through SIs requiring them to optimize the building's grid for modularity (e.g., using a 600mm module to maximize component inter-changeability) and to perform design audits for deconstructability. Conversely, the Owner is the financial and regulatory anchor, responsible for SIs within the Governance dimension, such as setting the minimum target for Residual Material Value (RMV) or requiring Performance-Based Contracting that incentivizes material efficiency. By defining these boundaries of responsibility, the framework minimizes the potential for strategic ambiguity, where CE goals are delegated vaguely to the "design team" and ultimately abandoned due to perceived complexity or cost.

4.1.2 The Interdependence of the Four Dimensions

A deeper analysis of the framework reveals that successful CE operationalization is non-linear and relies on the symbiotic relationship between the four core dimensions.

The Digital Enablement dimension acts as the necessary precondition for maximizing efficiency in the Material Flow and Systemic Design dimensions. Without the precise, auditable data flows provided by digital tools, any effort to reuse or reclaim materials is severely hampered by information asymmetry. For example, the SI mandating a BIM Manager to define an "end-of-life" layer within the model ensures that information about connection types, material manufacturer specifications, and potential contaminants is preserved, making the material bank accessible decades later. This goes significantly beyond standard BIM practice, which typically focuses on construction efficiency, pushing the model's utility into the facility management and deconstruction phases.

Furthermore, the Governance dimension dictates the successful integration of the other three. If the Owner, for instance, neglects to implement the SI requiring contractual incentives for achieving DfD targets, the Architect and Engineer will predictably revert to conventional, cheaper, and less reversible solutions. The framework thus recognizes that technology and design intentions alone are insufficient; they must be supported by a robust legal, financial, and contractual structure. This strategic integration is what distinguishes the MS-CEO framework from prior models which often suffered from being either too conceptual (lacking SIs) or too technical (lacking Governance alignment).

4.1.3 Case Study Illustration: Application in a Hypothetical Office Tower

To illustrate the framework's operational mechanics, consider its application in the design and planning phase of a hypothetical 15-story commercial office tower in a major metropolitan area.

A. The Challenge: The Client (Owner) has set an aggressive target: achieve a 60% material value retention rate after 50 years (a Governance SI). The initial design, utilizing a conventional concrete frame and composite cladding, was projected to achieve only 15% RMV.

B. Framework Application and Interventions:

1. Systemic Design Intervention (Architect & Structural Engineer):

- SI Applied: Structural Engineer must propose a structural system where 90% of connections are dry, mechanical, and accessible.
- Action: The team shifts from a concrete core with composite slabs to a hybrid steel-timber frame utilizing bolted connections throughout. The architect uses the framework's SI on modularity to ensure all interior walls, ceilings, and access floors are based on the same 1.2m grid, facilitating future space adaptation or demounting.

2. Material Flow Intervention (Architect & Material Supplier):

- SI Applied: Architect must specify structural flooring/facade components that are readily tradable on

existing secondary material markets.

- Action: The facade is designed using a proprietary curtain wall system that, under a newly negotiated "take-back" agreement (Governance SI), the supplier guarantees to repurchase at a defined residual value after 50 years. This requires the material supplier to provide verifiable Material Passports for the aluminum and glass components.

3. Digital Enablement Intervention (BIM Manager & Project Manager):

- SI Applied: BIM Manager must integrate all Material Passport data (manufacturer, toxicity, connection detail) into the Level of Information Need (LOIN) for the 75% design stage.
- Action: The project utilizes a BIM Object Library that enforces the input of all CE-relevant data fields before a component can be placed in the model. This guarantees that the final Material Passport is a complete, data-rich digital twin, satisfying the Owner's Governance SI for a high RMV.

C. The Outcome: By enforcing the SIs, the project successfully justified a \$4.5 million increase in initial CAPEX (for the hybrid structure and advanced connections) based on a projected \$22 million lifecycle saving over 50 years, primarily through a \$12\$ million increase in predicted Residual Material Value and \$10 million in reduced demolition and disposal costs. This example clearly demonstrates how the framework forces economic transparency and shifts the focus from initial cost to long-term value creation.

4.1.4 Detailed Sectoral Responsibility Analysis

The MS-CEO framework necessitates a redefinition of traditional project roles to successfully operationalize the CE. The following is an analysis of how the framework impacts key stakeholders:

The Owner/Client (Focus: Governance and Economics): The Owner's role shifts from a procurer of an asset to a curator of a material bank. The SIs place the onus on the Owner to champion the CE mandate from the outset. This includes:

- Mandating Life Cycle Costing (LCC): The requirement to move beyond capital expenditure and assess TCO forces a long-term value perspective.
- Selecting the Team on CE Criteria: SIs require CE experience and proposed solutions to be weighted heavily in the tender process, moving beyond simple cost-cutting.
- Assuming Responsibility for Material Passport Custodianship: The Owner is ultimately responsible for maintaining the digital data (Material Passport) and ensuring its transfer to the next property owner or facility manager, thereby protecting the embedded material value.

The Architect (Focus: Systemic Design and Aesthetics): The Architect's creative role is given new, measurable parameters. The framework's SIs transform abstract principles like modularity and flexibility into concrete design deliverables:

- Prioritizing Reversible Connections: The design must feature component access and separation, requiring the architect to integrate maintenance and deconstruction logistics into the building envelope and interior design.
- Material Health and Traceability: The Architect must verify the absence of 'red list' materials (toxic/non-recyclable) and ensure that all specified materials have a verifiable origin and composition suitable for a Material Passport.

The Structural/MEP Engineer (Focus: Technical Design for Deconstruction): This role undergoes the most dramatic technical shift. The SIs mandate a significant departure from conventional engineering practices:

- **Structural DfD (DfD-S):** The engineer must not only ensure structural integrity but also the deconstructability of the structure, actively seeking alternatives to composite elements and permanent bonding. This requires new skills in selecting and detailing bolted, clamped, or wedged connections.
- **MEP Services (DfD-MEP):** SIs require mechanical, electrical, and plumbing (MEP) systems to be easily separable from the structure (e.g., non-poured-in-place pipe chases, modular electrical harnesses) to allow high-value recovery of copper, metals, and specialized components.

The Project Manager/BIM Manager (Focus: Digital and Process Enablement): This role is critical for the framework's implementation success. The SIs emphasize data and process integrity:

- **CE Process Integration:** The Project Manager must integrate the MS-CEO SIs into the standard project schedule (e.g., "75% Design Review: DfD Checklist Sign-Off").
- **Data Gatekeeping:** The BIM Manager is the custodian of the Digital Enablement SIs, ensuring that all models contain the mandated non-geometric data essential for future material management.

In conclusion, the MS-CEO Framework operationalizes the Circular Economy by assigning clear, auditable, and interconnected SIs to all major stakeholders, thereby transforming the complex goal of circularity into a systematic, achievable set of design and planning deliverables.

4.2 Alignment with Global CE Principles and Existing Standards

The MS-CEO framework aligns strongly with the core tenets articulated by leading CE proponents. The emphasis on Systemic Design and DfD directly operationalizes the CE principle of designing out waste at its source, moving beyond simple end-of-pipe waste management. Furthermore, the framework's focus on information flow through Material Passports and BIM integration is instrumental in keeping materials and products in use at their highest value, enabling future reuse and remanufacturing opportunities.

Existing policy tools often focus on macro-level interventions, such as landfill taxes or procurement mandates. While necessary, these policies lack the micro-level guidance needed by design teams. The MS-CEO framework serves as a complementary micro-tool, providing the essential technical checklist and role clarity that translates the macro-policy goal into a project-specific action plan. For example, a governmental mandate for DfD (a macro policy) finds its practical execution guide in the MS-CEO framework's DfD SIs assigned to the Architect (massing, modularity) and the Engineer (connection type, material volume). The integration of Governance indicators, such as requiring life cycle costing (LCC) models, directly addresses the historical market failure where initial capital cost always triumphs over long-term resource efficiency.

4.3 Strategic Implications for Sustainable Design and Planning

The strategic implications of adopting the MS-CEO Framework are substantial, potentially shifting the industry from reactive sustainability measures to proactive, generative design.

4.3.1 Risk Mitigation and Value Retention

The implementation of Material Flow SIs, such as the preference for secondary or low-embodied carbon materials, serves as a vital risk mitigation strategy against future material price volatility and supply chain disruption. By pre-planning for material recapture and reuse at the design stage, a project effectively generates a future material asset. The framework facilitates this by quantifying and documenting this potential value upfront, thereby allowing project stakeholders, particularly the Owner, to calculate the Total Cost of Ownership (TCO) and the Residual Material Value (RMV), rather than being limited to the traditional initial capital expenditure (CAPEX) view. This advanced economic modeling is facilitated by the framework's Governance SIs that mandate the use of TCO and RMV calculations.

4.3.2 Enforcing Design for Deconstruction (DfD)

The framework's primary strength lies in its ability to enforce DfD beyond mere aspiration. A key indicator assigns the Structural Engineer the responsibility to produce a DfD checklist demonstrating, for example, that the project's structural system has a maximum number of four distinct connection types, all of which are reversible. This formalizes DfD, making it an auditable design deliverable, equivalent in importance to structural calculations or fire safety plans. Without such a framework, the engineer has no contractual obligation to consider the building's end-of-life, leading to the use of irreversible, material-contaminating connections (e.g., non-separable composite materials, adhesive bonds) that immediately render future high-value material recovery impossible.

4.3.3 Digital-Physical Synchronization

The synchronization of the Digital Enablement and Systemic Design dimensions is the future of sustainable practice. The framework mandates the use of Building Information Modeling (BIM) not just for clash detection, but as a central repository for the Material Passport data. This allows the design team to run simulated "deconstruction clash detection" in the digital twin, ensuring accessibility for future material removal. For example, the Architect must use the BIM model to verify that key reusable elements are accessible by standard dismantling equipment without damaging adjacent structures, a mandatory SI that elevates DfD from a guideline to a modeling requirement. The MS-CEO framework is designed to bridge the data gap between the digital design model and the physical, constructed reality.

4.4 Practical Barriers and Implementation Strategies

While the MS-CEO framework is validated as highly relevant and feasible, its successful deployment will be moderated by several persistent practical barriers.

- **Supply Chain Maturity:** The lack of a mature, standardized, and competitive supply chain for high-quality secondary materials remains a significant barrier to maximizing the Material Flow SIs. The implementation strategy here requires project teams, mandated by the Owner via the Governance SIs, to aggregate demand through collaborative procurement models, signaling a long-term market need to suppliers and deconstruction firms.
- **Initial Cost Premium:** CE strategies, such as DfD and the use of modular, reversible systems, are often associated with a higher initial CAPEX compared to traditional "cheap and disposable" construction methods. The counter-strategy, built into the Governance dimension, is the mandatory shift to Life Cycle Costing (LCC). By contractually obligating the project team to calculate the cost savings from material value retention, reduced demolition fees, and lower operational energy use (due to quality materials), the MS-CEO framework reframes the higher CAPEX as a prudent long-term investment.
- **Regulatory and Legal Uncertainty:** Existing building codes and contract law were drafted for a linear economy. Issues like the transfer of liability and warranties for reused components, and the standardization of material certification for secondary materials, introduce legal friction. The framework addresses this by including SIs that mandate early consultation with legal experts to clearly define responsibilities related to material warranties and liability transfer for components intended for future reuse.

4.5 Limitations and Future Research

The primary limitation of this study resides in its validation methodology, which relied on the Delphi method to establish consensus on the framework's theoretical relevance and practical feasibility. While this approach is robust for expert-driven validation, the MS-CEO Framework has not yet been subjected to a longitudinal, real-world application to measure its operational impact on material circularity rates, actual waste reduction figures, or project cost and schedule outcomes. The expert panel's composition, while international, may also introduce a degree of geographic or regulatory bias, particularly concerning the feasibility of SIs tied to emerging supply chain models.

Future research should focus on:

1. Empirical Case Studies: Conducting action research where the MS-CEO Framework is implemented in parallel with traditional methods on pilot projects to quantify the differences in material value retention and project outcomes.
2. Tool Development: Creating digital tools, potentially BIM plug-ins, that can automate the tracking and reporting of the MS-CEO SIs, reducing the manual burden on project managers and designers.
3. Refinement for Scale: Adapting and testing the framework specifically for smaller-scale residential and renovation projects, where resource and budget constraints present unique operational challenges.

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