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Integrating Design for Manufacturing, Assembly, and Disassembly to Accelerate Circular Economy in Construction: A Conceptual Framework

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ABSTRACT: The construction industry continues to rely on linear "take–make–dispose" models that generate significant waste and resource inefficiency. This paper proposes a conceptual framework integrating Design for Manufacturing and Assembly (DFMA) and Design for Disassembly (DFD) to accelerate the transition toward circular construction. Using a conceptual–illustrative approach, the study synthesises key insights from design theory and circular economy principles to explain how DFMA enhances production efficiency while DFD ensures material recoverability and reuse. The proposed framework connects design efficiency, material value retention, and policy readiness through enabling mechanisms such as modular standardisation and digital modelling. Findings indicate that integrating DFMA and DFD redefines efficiency from linear productivity to regenerative value creation, transforming buildings into dynamic material banks. The study concludes that design integration offers a strategic pathway for developing economies, such as Vietnam, to achieve industrialised, low-carbon, and circular construction systems.

KEYWORDS: DFMA, DFD, Life Cycle, Sustainable Construction, Circular Economy, Vietnam.

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Introduction

The construction industry remains one of the world's most resource-intensive and environmentally burdensome sectors. Despite recent advances in digitalisation and green building technologies, the prevailing linear model of "take–make–dispose" continues to dominate project delivery. Globally, construction and demolition activities account for a massive share of total solid waste generation and consume over 30% of extracted raw materials (Benachio et al., 2020). This linear pattern not only accelerates resource depletion and landfill saturation but also undermines the long-term retention of value within the built environment. In developing economies such as Vietnam, the situation is exacerbated by rapid urbanisation, fragmented supply chains, and limited mechanisms for material recovery, resulting in a "build-and-discard" culture that contradicts sustainability ambitions (Van Tuan et al., 2018).

Against this backdrop, Design for Manufacturing and Assembly (DFMA) and Design for Disassembly (DFD) emerge as transformative design philosophies that can bridge the gap between industrial efficiency and circular resource management. Originally conceived within the manufacturing sector, DFMA aims to optimise products for simplified fabrication and assembly, thereby reducing material waste, labour costs, and on-site variability (Bock, 2015). When applied to construction, DFMA promotes standardisation, modularisation, and off-site production, enabling faster, safer, and more predictable project delivery. Complementing this approach, DFD extends design consideration to the end-of-life stage by facilitating selective disassembly, reuse, and recycling of building components(Akinade et al., 2017). Together, DFMA and DFD encapsulate a "whole-life design logic", ensuring that efficiency in manufacturing is matched by recoverability at the end of life.

However, despite growing recognition of their environmental and operational benefits, the integration of DFMA and DFD remains conceptually fragmented. The two design paradigms are often treated in isolation—DFMA within discussions of productivity and cost reduction, and DFD within the domain of sustainability and waste minimisation (Hossain & Ng, 2018). This separation has led to a lack of systemic frameworks that connect early-stage design optimisation with end-of-life material recovery, both of which are essential to achieving the Circular Economy (CE) vision for the built environment. While circular construction emphasises material loops and resource efficiency, most research and policy instruments focus on recycling or material substitution rather than the design integration mechanisms that make circularity practically achievable (Eberhardt et al., 2022).

Moreover, current literature provides limited insight into how DFMA–DFD integration transforms the economic and institutional logic of construction systems. The dominant discourse still frames DFMA as a productivity tool rather than as an enabler of circularity. In contrast, a growing body of international work highlights the potential of design integration — supported by digital modelling (BIM), product data traceability, and modular standardisation — to generate circular value chains where buildings function as material banks(de Lima et al., 2023). Yet, for many developing contexts, such as Vietnam and other Southeast Asian nations, the lack of regulatory incentives, digital capabilities, and disassembly-friendly codes continues to hinder the transition from linear to circular construction.

Accordingly, this paper seeks to address this research gap by developing a conceptual framework that links DFMA–DFD integration with the principles and enablers of Circular Construction.

Through a comprehensive literature review, the study synthesises the interrelations among design standardisation, manufacturing efficiency, and life-cycle material recovery. It argues that integrating DFMA and DFD at the design stage can reconfigure construction economics from one based on throughput and extraction to one centred on resource regeneration and value retention. By articulating this integration, the paper contributes to the emerging discourse on industrialised and circular construction– a paradigm essential to achieving both decarbonization and resource circularity in the global built environment.

Research Aim, Questions and Approach

This study aims to develop a conceptual framework that explicates how the integration of DFMA and DFD can accelerate the transition from linear to circular construction systems. By synthesising insights from design science, construction economics, and circular economy literature, the study elucidates the mechanisms through which design integration influences material efficiency, value recovery, and systemic transformation.

To achieve this aim, the study addresses three interrelated research questions (RQs):

RQ1: How do DFMA and DFD, respectively, contribute to the principles and outcomes of circular construction across different life-cycle stages?

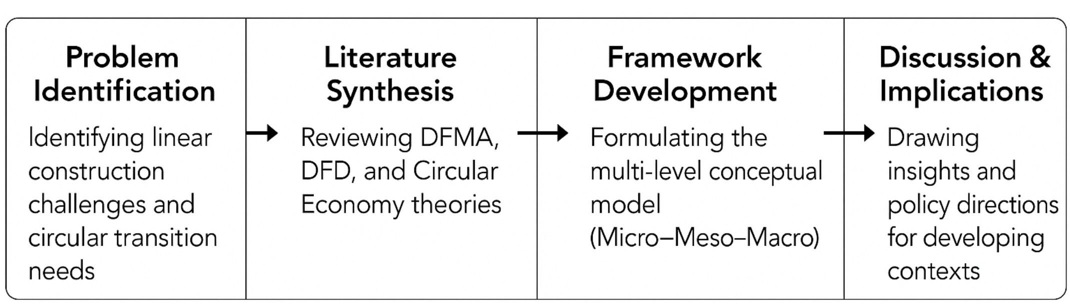
RQ2: Through what design, technological, and organisational mechanisms does the integration of DFMA–DFD enable value retention and resource circulation within the built environment?

RQ3: What are the key institutional, policy, and capability factors that condition the successful adoption of DFMA–DFD integration in developing construction markets such as Vietnam?

The research process is outlined in Figure 1.

Figure 1

Research process



Source: author(s) own development

This study employs a four-step conceptual and illustrative research approach. It begins with synthesising insights from DFMA, DFD, and Circular Economy literature, followed by the development of a multi-level conceptual framework that illustrates the mechanisms qualitatively. Finally, it discusses theoretical and policy implications for circular construction in developing contexts.

Theoretical Background

Design for Manufacturing and Assembly (DFMA) and Design for Disassembly (DFD) originate from the broader "Design for X" paradigm, which aims to optimise products for efficient production, assembly, and end-of-life management. In construction, DFMA shifts conventional on-site, craft-based processes toward industrialised, off-site production through modularisation, standardisation, and digital design (Montazeri et al., 2024). The approach enhances productivity, minimises waste, and enables precise, repeatable assembly—key characteristics of industrialised and sustainable construction systems.

Complementing DFMA, DFD extends the design horizon beyond production to material recovery and reuse. By anticipating disassembly, DFD ensures that components can be separated without damage, reused, or remanufactured for future use. This principle transforms buildings into dynamic material banks, where materials retain value across multiple life cycles (Akbarieh et al., 2020). Non-destructive connections, reversible joints, and digital documentation—such as BIM and material passports—enable traceability and facilitate closed-loop material flows.

When integrated, DFMA and DFD form a closed-loop design continuum that connects manufacturing efficiency with end-of-life recoverability. DFMA reduces waste and cost during construction (Rethink–Reduce in the 9R hierarchy), while DFD promotes reuse, refurbishment, and recycling (Reuse–Refurbish–Remanufacture–Recycle). Their combination operationalises circularity not as a post-construction process but as a design principle embedded from project inception.

Within Circular Economy (CE) theory, the built environment is recognised as both a major resource consumer and a key driver of systemic transformation (Ellen MacArthur Foundation, 2021). Circular construction operates across micro (project), meso (firm/supply chain), and macro (policy/system) levels (Hart et al., 2019). DFMA–DFD integration links these scales by translating policy goals into design strategies and industrial capabilities. At the project level, it fosters modular adaptability; at the supply chain level, it enables collaboration and material traceability; and at the policy level, it aligns design innovation with regulatory frameworks.

However, significant barriers remain. Construction procurement remains fragmented, with regulations rarely addressing disassembly, and the valuation of recovered materials is limited. Without supportive standards or economic incentives, DFMA–DFD practices remain isolated innovations. Digital technologies, such as BIM and Digital Twins, offer crucial infrastructure for managing design data and lifecycle traceability; however, their adoption in developing contexts is still in its early stages.

Theoretically, integrating DFMA and DFD signifies a shift from linear efficiency to regenerative efficiency—from maximising output to maximising value retention. This redefinition aligns with sustainability transition theory, suggesting that design integration is both a technical and institutional innovation. By merging the industrial logic of DFMA with the regenerative logic of DFD, construction can evolve into a circular, low-carbon, and data-driven ecosystem. This conceptual understanding provides the foundation for the next section, which introduces a framework linking DFMA–DFD integration with circular construction outcomes in emerging economies.

Research Results

This paper adopts a conceptual–illustrative approach to develop a multi-level framework that explains how DFMA–DFD integration drives circular construction. The framework aligns with the three-tier structure of the Circular Economy (CE) — micro, meso, and macro levels—highlighting how design integration scales from project practice to institutional transformation. Rather than an exhaustive review, the study draws on core literature in design theory, manufacturing, and circular construction to synthesise a unified model.

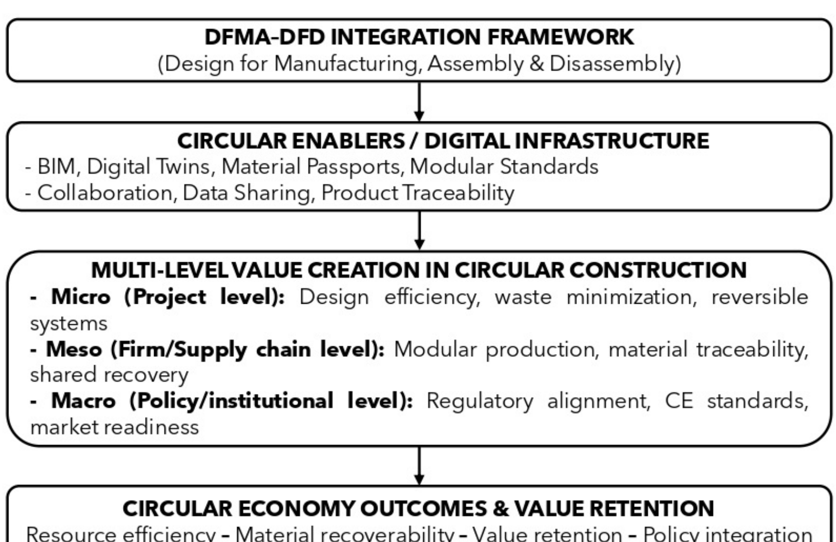
At its core, the framework conceptualises DFMA–DFD integration as the starting point that links design logic with circular outcomes through digital and organisational enablers such as Building Information Modelling (BIM), Digital Twins (DT), material passports, and modular standards. These digital infrastructures enable collaboration, data exchange, and material traceability across life-cycle stages and between industry actors.

The framework operates across three interconnected levels:

- Micro (Project level): DFMA enhances constructability, reduces material waste, and enables modular assembly; DFD ensures selective disassembly and reuse.
- Meso (Firm/Supply chain level): DFMA promotes mass customisation and shared component standards; DFD enables inter-firm material recovery and tracking across projects.
- Macro (Policy/institutional level): Aggregated DFMA–DFD data support policy design, CE regulation, and resource planning for recycled material markets.

Figure 2.

Multi-Level Conceptual Framework Linking DFMA–DFD Integration with Circular Construction Outcomes



Source: author(s) own development

This conceptual model provides a heuristic foundation for future empirical studies. It links design innovation with systemic change, clarifying how micro-level efficiency, meso-level coordination, and macro-level governance interact to achieve regenerative, low-carbon construction systems.

This conceptual approach provides a theoretical basis for future empirical inquiry. It can guide researchers in testing relationships between DFMA–DFD integration and circular performance indicators such as waste reduction, cost efficiency, and material recovery rates. For policymakers and practitioners, the framework provides a structured approach for integrating circular design principles into national standards, procurement systems, and training programs, particularly in developing construction markets such as Vietnam.

Discussion

The proposed framework illustrates how DFMA–DFD integration functions as a design-driven engine of circularity across three interdependent tiers.

At the micro level, DFMA optimises design and assembly to reduce waste and improve constructability. DFD complements this by ensuring that components can be dismantled and reused later. Together, they internalise the 9R strategies—Rethink, Reduce, Reuse, and Remanufacture—within project design, turning efficiency into regenerative value.

At the meso level, DFMA–DFD integration extends to firm and supply-chain collaboration. Standardised modules, interoperable data formats, and digital twins enable shared logistics and recovery networks. This level represents the operational bridge where digital traceability and collaborative production translate design efficiency into tangible circular flows of materials and components.

At the macro level, DFMA–DFD integration provides policymakers with the data infrastructure needed to develop CE-aligned regulations, material recovery markets, and fiscal incentives. For example, national digital construction policies—such as Vietnam's Decision No. 926/QĐ-BXD (2024)—can embed DFMA–DFD criteria within BIM mandates and green building codes to institutionalise circular design practices.

Collectively, these three levels reveal that circular construction is not achieved solely through end-of-life waste management, but rather through the integration of systemic design. DFMA initiates efficiency; DFD closes the loop; digital technologies connect the entire value chain. The result is a regenerative construction ecosystem where projects, firms, and institutions co-evolve toward industrialised and circular outcomes.

Conclusions

This study develops a conceptual framework illustrating how the integration of Design for Manufacturing and Assembly (DFMA) and Design for Disassembly (DFD) can accelerate circular construction. Using a conceptual–illustrative approach, it identifies three interrelated dimensions—design efficiency, material recoverability, and policy readiness—as the foundations for transforming linear construction into regenerative systems. DFMA promotes industrialised efficiency through modularisation and waste reduction, while DFD ensures value recovery by enabling selective disassembly and component reuse. Supported by digital tools such as BIM and material passports, DFMA–DFD integration redefines efficiency from rapid production to sustained value retention.

The framework contributes theoretically by linking industrial productivity and circular sustainability, offering practitioners a guide to embed circularity at the design stage. For policymakers, it underscores the need for standards, incentives, and digital infrastructure to facilitate widespread adoption. Overall, DFMA–DFD integration represents a design-led pathway for achieving industrialised, low-carbon, and circular construction in emerging economies.

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