

Digital Platforms for Circular Modular Construction: Benefits, Barriers, and Practical Pathways

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Abstract

This study examines the role of digital platforms in supporting the integration of Circular Economy (CE) principles within Modular and Offsite Construction (MOC). While MOC is often associated with waste reduction and production efficiency, its long-term sustainability depends on deliberate strategies to extend material lifecycles, enable reuse, and ensure institutional and market acceptance. The study adopts a narrative literature review approach, drawing on English-language sources published between 2015 and 2025, primarily identified through Google Scholar and Scopus and expanded through iterative reference tracing across themes related to CE, MOC, digital technologies, material traceability, and social dimensions of construction. The review examines the roles of Building Information Modeling (BIM), sensors and the Internet of Things (IoT), Computer Vision (CV), blockchain, and material passport systems in supporting traceability, component reuse, and stakeholder coordination when integrated within interoperable data infrastructures and governance arrangements. The analysis identifies potential contributions, including improved lifecycle data integration, enhanced quality control processes, and more consistent documentation of reused components. However, most reported applications remain context-specific and are predominantly documented through pilot projects, demonstrators, or vendor-led initiatives rather than established industry practice. Frequently reported barriers include high implementation costs, limited interoperability, data governance challenges, regulatory uncertainty, and organizational resistance to reuse and automation. The study highlights that digital integration alone is insufficient to ensure circular outcomes. Progress toward CE–MOC adoption is shaped by governance arrangements that connect technical capabilities with institutional frameworks, market incentives, and social considerations. By outlining enabling conditions and limitations identified in the literature, this study provides insights for practitioners, policymakers, and researchers seeking to advance circular construction and emissions reduction through coordinated, evidence-based approaches.

Keywords Circular Economy (CE) · Modular and Offsite Construction (MOC) · Building Information Modeling (BIM) · Digital Traceability · Sustainable Development Goals (SDGs)

1. Introduction

The construction sector is one of the largest contributors to global environmental pressures. According to the UNEP Global Status Report for Buildings and Construction 2024/2025 (UCL et al., 2025), the built environment accounts for approximately 32% of global energy use and nearly 34% of energy-related CO₂ emissions in 2023, making it the largest emitting sector globally. When embodied carbon from construction

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material production and associated processes is included, total emissions reach 39% of global-energy related CO₂, with 28% originating from building operations and 11% from materials and construction activities. and the construction sector also generates around two billion tons of construction and demolition (C&D) waste annually, representing roughly one-third of global waste (Atradius N.V., 2023; UCL et al., 2025). Conventional on-site construction methods exacerbate these impacts through inefficient resource utilization, excessive waste generation, and limited capacity for material recovery, underscoring the need for more sustainable construction approaches (Alawneh et al., 2019; Garusinghe et al., 2023; Ginga et al., 2020).

Modular and Offsite Construction (MOC) has emerged as an alternative to conventional construction practices. By fabricating building components in factory-controlled environments and assembling them on-site, MOC reduces quality variability, minimizes material waste, and improves production efficiency (Garusinghe et al., 2023; Jayawardana et al., 2023c). Centralized production also facilitates integration of emissions monitoring, renewable energy systems, and waste-filtration technologies that are difficult to implement in conventional projects (Tavares et al., 2021; Zhang et al., 2022). However, these advantages do not automatically translate into circular outcomes, as many modular systems remain optimized for speed and cost rather than for disassembly, reuse, or long-term material recovery.

MOC alone does not guarantee sustainability. Without integration into a broader circular framework, modular construction risks remaining an efficiency-driven approach that fails to preserve material value across the building lifecycle. A narrow focus on economic and environmental efficiency may also overlook social dimensions, including labor conditions, cultural acceptance, and enabling policy frameworks (Brandão and Verissimo, 2024; Ly et al., 2024; Otasowie et al., 2025).

The Circular Economy (CE) provides principles for minimizing waste, regenerating resources, and keeping materials at high utility for as long as possible. Unlike the linear “take–make–dispose” model, CE emphasizes closed-loop strategies such as reuse, repair, refurbishment, remanufacturing, and recycling, often captured under the “9R” framework: Rethink, Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Recycle, and Recover (Jayawardana et al., 2023c; Ly et al., 2024). As illustrated in Figure 1, embedding CE strategies within MOC can, under appropriate design, governance, and market conditions, extend material lifespans, reduce dependence on virgin resources, and lower environmental burdens.

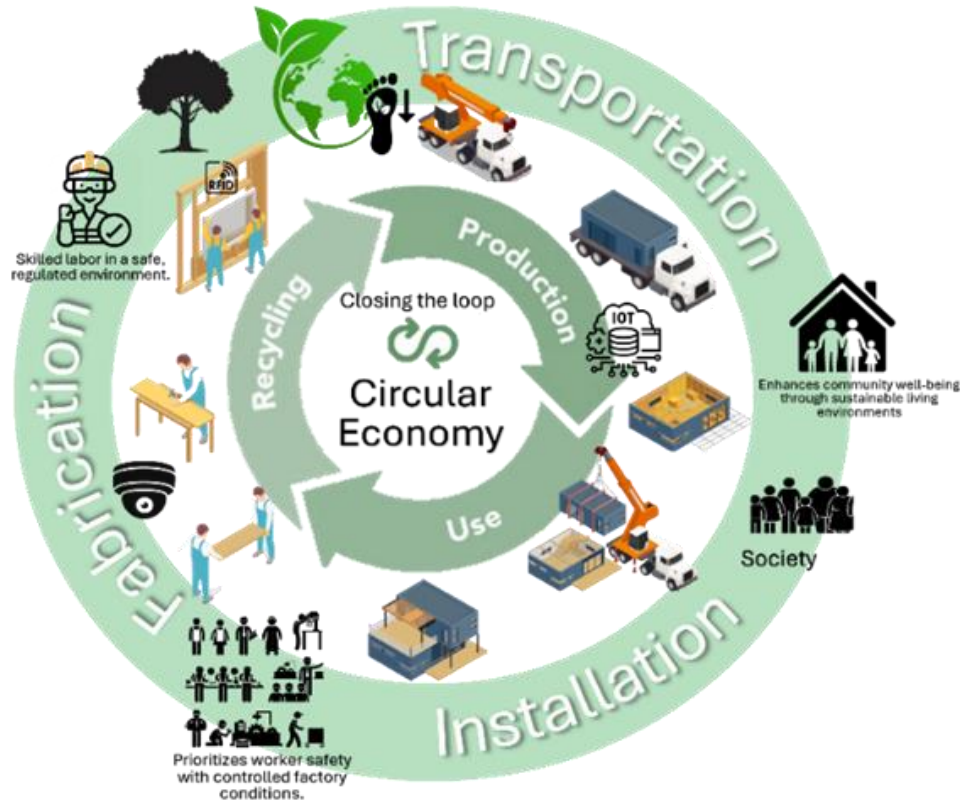


Figure 1. CE integration across MOC lifecycle stages (fabrication → end-of-life). Arrows represent material/value flows; icons denote environmental, economic, social dimensions; digital tools (BIM/IoT) enable traceability. Demonstrates circular strategies must be intentionally embedded at each stage.

While MOC's factory-based precision and modular design are often presented as naturally aligned with CE principles, this alignment is not automatic and is subject to structural tensions in practice. Many modular systems prioritize construction efficiency and cost reduction over disassembly, reuse, or long-term material recovery. Although complementarities between MOC and CE are frequently cited, they are not consistently realized in practice. MOC can facilitate design-for-disassembly and component reuse, but CE benefits materialize only when circular strategies are intentionally embedded through design decisions, certification mechanisms, and circular business models. Under these conditions, CE–MOC can contribute not only to environmental objectives but also to social and economic outcomes, including localized supply chains, regional development, and improved health and safety through reduced on-site hazards (Zhuang et al., 2023). Nevertheless, significant barriers persist, including market resistance to reused materials, high upfront investment requirements, interoperability challenges, and regulatory gaps.

Despite growing interest, the role of digital platforms in translating CE principles into actionable and scalable practices within MOC remains insufficiently articulated and empirically grounded. Digital technologies such as Building Information Modeling (BIM), sensors, Computer Vision (CV), and blockchain are increasingly explored as enabling infrastructures linking design, monitoring, and traceability across lifecycle stages, yet their effectiveness depends on equitable deployment and robust governance protocols (Bozorgzadeh and Umar, 2023; Kebede et al., 2024; Mäkitie et al., 2023). Risks associated with data privacy, surveillance, and uneven digital infrastructure also require consideration. Evidence from practice suggests that successful circular systems often rely as much on trust, cultural readiness, and supportive institutional context as on technological capability (Paquin et al., 2014).

Accordingly, this paper adopts a balanced perspective in which digital innovation is considered alongside policy reform, institutional support, and stakeholder engagement. Drawing on a narrative synthesis of the literature, the study evaluates benefits, barriers, and enabling conditions associated with CE–MOC, with particular attention to the role of digital platforms in aligning governance, equity, and traceability.

The contribution of this study lies in integrating fragmented debates on digitalization, CE, and MOC into a unified framework focused on resource conservation and material reuse. Unlike earlier studies that emphasize either technological or environmental aspects, this study highlights the equally critical social and cultural drivers that enable large-scale adoption. In doing so, it provides both conceptual clarity and practical pathways for advancing CE–MOC as a potential systemic transition, contingent on institutional alignment, governance capacity, and digital integration, toward more resource-efficient and low-carbon construction.

2. Methodology

This study adopts a narrative literature review approach to examine the integration of CE principles within MOC. The review focused on English-language literature published between 2015 and 2025, primarily identified through Google Scholar and Scopus. The process began with key publications addressing CE–MOC, digital technologies, and modular construction, followed by iterative exploration of reference lists and related citations to capture adjacent and interdisciplinary discussions.

As the review progressed, the scope expanded across interconnected themes, including CE strategies, MOC practices, digital tools and platforms, material passports and registries, certification and standards, and social dimensions such as workforce inclusion, diversity, and trust. Rather than applying formal inclusion–exclusion criteria, the literature was assembled iteratively to enable connections across domains and to support the development of the phased framework presented in this manuscript. Reported applications were interpreted cautiously, with attention to context, maturity, and distinctions between conceptual proposals, pilot studies, and early-stage implementations.

3. Modular Construction and Circular Economy Synergies

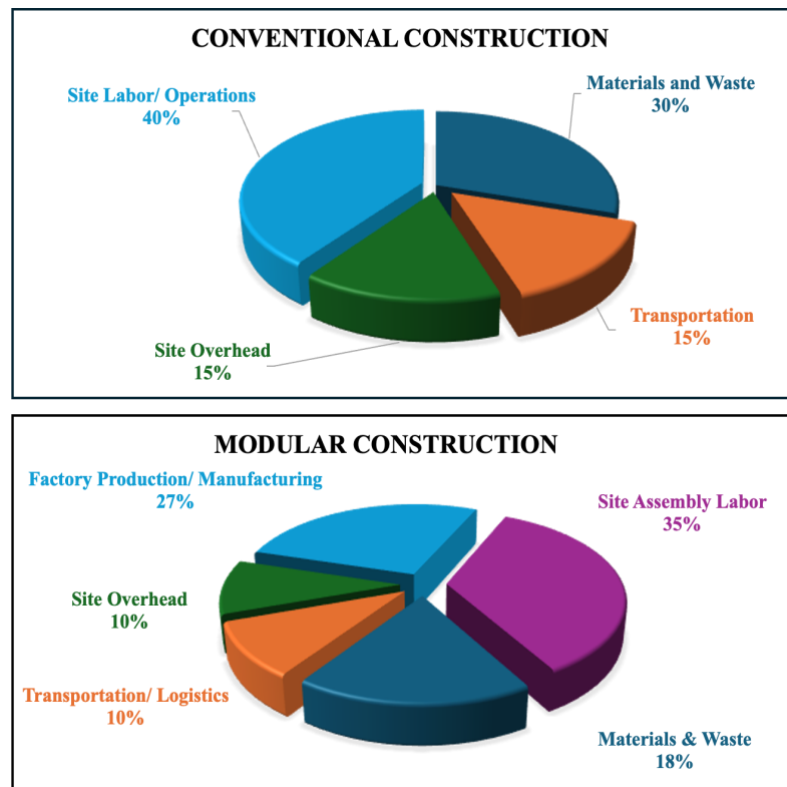
MOC, also known as industrialized or prefabricated construction, involves producing building modules in factory-controlled environments and subsequently transporting them for on-site assembly (Molavi and Barral, 2016; Yang et al., 2017). This approach is often reported as enhancing construction quality, efficiency, worker safety, and overall sustainability. Factory-based production provides a level of precision and standardization that is difficult to achieve through conventional on-site techniques. As a result, MOC can reduce material

waste, lower rework rates, and shorten project timelines, thereby potentially lessening environmental impacts (Hossain and Thomas Ng, 2019). These outcomes stem from rigorous quality control and measurement protocols that are integral to off-site production (Liu et al., 2022; Yang and Lu, 2023a, 2023b). While standardized processes underpin these efficiencies, modules can still be customized to meet project-specific requirements, which demands adaptable quality systems within the standardized framework, while in some cases, standardized module dimensions and composite material specifications may increase transportation intensity or reduce recyclability compared with non-modular alternatives (Botchway and Pan, 2022; Yang and Lu, 2023a). However, these efficiencies alone do not guarantee circular performance, as modular systems may still rely on composite materials, linear supply chains, or limited reuse pathways if circular objectives are not explicitly prioritized.

3.1. Efficiency and Sustainability Benefits

Comparative studies suggest MOC's ability to redistribute project costs and significantly reduce waste compared with conventional construction. For instance, modular construction has been quantified to reduce the overall weight of waste by up to 83.2% in analyzed cases, corresponding to a 47.9% decrease in the cost of waste for large structures, noting that outcomes vary by project scale and material costs assumptions (Loizou et al., 2021). With environmental analysis reports that in distance-location scenarios transport to site can rise to ~25% of embodied energy and ~27% of embodied Greenhouse gas emissions (GHG), reflecting sensitivity to distant, transport mode, and volumetric module logistics (Bertram et al., 2019; Zohourian et al., 2025). However, literature does not support a universal reduction in transportation cost: multiple-case cost analyses identify transportation as a major expense item in MOC (Mao et al., 2016), and cost-benefit reports transportation can account for ~10% of total cost for typical prefabricated components, with some survey-based research suggesting ~19-20% in specific contexts (Hong et al., 2018). Industry reports further note that logistics can increase total project cost by up to ~10% in locations with restrictive transport regulations, particularly when large 3D modules must be moved (Bertram et al., 2019). Accordingly, transport and logistics in MOC should be treated as typology- and distance-sensitive trade-off (e.g., factory location, route constraints, module dimensions and weight, and backhauling opportunities) rather than a consistent saving. (Garusinghe et al., 2023; Loizou et al., 2021; Romero Quidel et al., 2023a; Sullcapuma Morales, 2023). These efficiencies and trade-offs reflect the operational advantages of centralized production, integrated logistics, and resource management as summarized in Figure 2.

Figure 2. Average cost distribution: conventional construction (top) vs. modular (bottom). Percentages are based on published studies. In the conventional case, roughly 40% of costs are site labor/operations, 30% materials and waste, 15% transportation, and 15% site overhead. In modular construction, costs shift toward off-site processes: about 35% is site-assembly labor, 27% factory manufacturing, 18% materials/waste, and 10% each for transportation/logistics and site overhead.



Beyond cost savings, MOC may contribute to environmental sustainability through lower greenhouse gas emissions, minimized on-site disruption, and extended material service life. Table 1 compares MOC with conventional approaches across key dimensions, including waste reduction, overall efficiency, environmental impact, design flexibility, quality assurance, and worker safety. Notably, it highlights how the durability and reuse potential of modular strategies can align with CE principles (Kyrö et al., 2019; Machado and Morioka, 2021).

Table 1. Quantitative values represent indicative ranges reported in the literature and should be interpreted as typical orders of magnitude rather than universal outcomes. Comparisons assume conventional site-based construction as the reference case. Actual performance depends on project type, supply chain maturity, regulatory conditions, and system boundaries used in environmental assessments.

Aspect	MOC	Conventional Construction	References
Construction Time	Studies report 20–50% shorter project durations as off-site fabrication occurs concurrently with site preparation, allowing parallel workflows and minimizing weather delays.	Construction activities occur sequentially on-site, limiting schedule compression and increasing vulnerability to weather and coordination delays.	(Bertram et al., 2019; Sullcapuma Morales, 2023; Zohourian et al., 2025)
Cost & Efficiency	Modular requires higher upfront cost for production and logistics, but tends to lower total costs. For example, one analysis found that factory procurement and reuse cut waste by up to ~20%. By moving up to 80% of labor into the factory, on-site labor needs drop (estimated ~25% labor cost reduction).	Conventional incur higher on-site labor, waste, and overhead. On-site overhead (security, supervision, scaffolding) adds roughly 10–15% to project cost due to the longer schedule. Total costs are generally higher or more unpredictable than modular projects.	(Bertram et al., 2019; Tavares et al., 2021)
Environmental Impact	Factory-controlled production improves material efficiency and reduce waste by 30–60% and carbon emissions by about 20–40% through controlled manufacturing and optimized logistics.	On-site processes generate large amounts of waste (report as 25–35 % of materials) and produce more noise and dust; little scope for material reuse.	(Pervez et al., 2021; Romero Quidel et al., 2023b; Wang et al., 2025; Zhang et al., 2022)
Flexibility	Modules allow 70–90% component reuse potential and enable relocation or reconfiguration with minimal demolition.	Structural modifications often require demolition or major reconstruction, leading to higher material loss and costs.	(Chourasia et al., 2023; Shooshtarian et al., 2025)
Quality Control	Factory production lines maintain dimensional tolerances of ± 2 –3 mm, compared to typical on-site tolerances of ± 5 –10 mm. Multi-stage inspections at each manufacturing step reduce defect and rework rates by 30–50%.	On-site construction tolerances typically range from ± 5 –10 mm, with higher variability due to manual installation, weather exposure, and sequential work processes. Rework rates can reach 5–15% of project cost.	(Bertram et al., 2019; Panahi et al., 2023; Wang and Tao, 2019)
Worker Safety	Work happens in controlled factories; modules are assembled at ground level and typically only 2.4–3 m (8–10 ft) tall. This reduces the need for ladders and scaffolding and limits exposure to weather and height.	On-site workers are exposed to manual handling, height and weather hazards. Statistics show that 65 % of construction workers use scaffolds and ladders account for 24 % of fatal falls in construction, while 15 % of fatal falls involve scaffolds.	(Fard et al., 2017; Lopez and Froese, 2016; Shahzad et al., 2023)

3.2. Case Evidence and Comparative Analysis

The benefits of MOC are well illustrated through real-world applications. The Westin Riverfront Resort, a nine-story luxury hotel (~50,500 m²), adopted a precast concrete modular system comparable to flat-slab construction. This strategy enabled the project to overcome seasonal weather constraints, finish two weeks ahead of schedule, reduce labor costs, and accelerate revenue generation (Hanlon et al., 2008).

Similarly, the reconstruction of a hotel complex in Volgograd demonstrated MOC's waste reduction capacity. Precision factory cutting minimized on-site waste and simplified recycling of modified components, reinforcing modular construction's environmental advantages (Voronkova et al., 2021).

These cases confirm that MOC can deliver measurable sustainability and efficiency gains under specific project conditions. However, even greater benefits can be achieved when MOC is embedded within CE

strategies. Through design for disassembly, reuse, refurbishment, and repurposing, modular components can extend their service life and reduce dependence on virgin resources (Allam and Nik-Bakht, 2023). Integrating CE principles also mitigates the generation of construction and demolition waste, a major source of environmental degradation (Elghaish et al., 2023, 2022). In parallel, digital design tools and automated cutting systems further enhance material utilization, minimizing off-cuts and optimizing energy consumption in production (Dams et al., 2021; Ostapska et al., 2024).

Taken together, these examples underscore MOC's dual potential: as a present-day method for improving construction efficiency and as a strategic foundation for embedding CE principles to achieve systemic sustainability in the built environment. Additional CE-MOC cases demonstrate realized circularity. The Kamibox project in the Netherlands used modular steel frames with material passports, achieving 80% disassembly/reuse rates via BIM-blockchain integration (Honic et al., 2024). Similarly, Volume Building Company's "Chapter One" housing achieved 90% material recovery through design-for-disassembly, reducing virgin steel needs by 65% (Elghaish et al., 2023). The next section examines the digital technologies that can enable this transition by strengthening traceability, stakeholder coordination, and resource recovery.

4. Digital Enablers for CE-MOC

Technological advancements, including BIM, sensors and the Internet of Things (IoT), CV, and blockchain, are increasingly promoted as enablers of CE practices in MOC. These tools can improve precision, enhance quality assurance, and support lifecycle monitoring and material traceability across the construction lifecycle (Han et al., 2023; Kovacic et al., 2020). However, their adoption faces challenges such as high implementation costs, risks to data privacy and cybersecurity, and limited interoperability across platforms (Liu et al., 2021; Uçar et al., 2020). Critically, the effectiveness of these technologies depends not only on their technical capabilities, but also on how they are coordinated and integrated across stakeholders through shared data structures and agreed protocols. In this context, "digital platforms" refers to the integrated system that connects individual technologies (BIM, IoT, CV, blockchain) to enable consistent data exchange and coordinated implementation across the CE-MOC lifecycle (Kovacic et al., 2020). Furthermore, many claims regarding effectiveness derive from early-stage prototypes or vendor-led demonstrations rather than validated, large-scale applications (Bartlett et al., 2020; Dou et al., 2024). This section discusses how each technology may contribute to CE-MOC and highlights governance considerations necessary for responsible and equitable deployment.

4.1. Digital Platforms – Interoperability between Technologies

The term, "digital platforms" in CE-MOC literature encompasses individual digital tools and the integrated governance system that orchestrates them. Following recent frameworks in circular economy study (Kovacic et al., 2020; Liu et al., 2021), a digital platform is infrastructure characterized by three attributes: (1) standardized data protocols and open interfaces that enable seamless information exchange across tools; (2) multi-stakeholder coordination mechanisms that align incentives across manufacturers, designers, logistics providers, reuse operators, and regulators; and (3) institutional arrangements that define data ownership, access rights, and value distribution. Permissioned blockchain has been proposed as a way to support controlled data sharing among stakeholders, while IoT can monitor project progress and BIM can provide a medium for digital integration (Liu et al., 2021). The digital platform, by contrast, transcends individual technologies by establishing the governance conditions necessary for them to function as a coherent system (Kovacic et al., 2020). Without explicit platform governance, individual technologies cannot achieve the cross-organizational data flows and stakeholder alignment necessary for circular material recovery (Han et al., 2023; Uçar et al., 2020).

4.2. BIM for Lifecycle Integration

BIM creates detailed digital representations of buildings and individual components, enabling precise prefabrication, efficient on-site assembly, and significant waste reduction (Olawumi et al., 2018; Takyi-Annan and Zhang, 2023). When combined with sensor and CV systems, BIM facilitates real-time monitoring to ensure continuous compliance with design and quality standards (Celoza and Lopez Alvarez de Neyra, 2024; Sun et

al., 2017). It also enhances collaboration among stakeholders by centralizing project data, reducing coordination errors, and preventing scheduling conflicts (Çetin et al., 2022; De Wolf et al., 2024; Foo et al., 2023). In addition, BIM can embed lifecycle data into digital models, supporting resource planning aligned with CE principles and enabling material reuse, design-for-disassembly, and long-term asset management (Carvalho et al., 2024; Chen et al., 2018; Li et al., 2021).

4.3. IoT and Sensors for Predictive Monitoring

Embedding sensors within prefabricated components provides real-time data on structural stress, moisture levels, and temperature, enabling predictive maintenance and improved durability (Vandi et al., 2024). Integrated with IoT and RFID systems, these sensors enhance supply-chain transparency and support continuous tracking of materials throughout their lifecycle (Cawley, 2018; Copeland and Bilec, 2020; Rehman et al., 2024).

Typical applications include load and deformation monitoring, early mold detection, and quality control during concrete curing (Avramov et al., 2025; Rao et al., 2022). These applications are relevant to both conventional and MOC. However, MOC shift several high-consequence risks into logistics and assembly stage, prefabricated modules can experience transportation-induced vibrations and handling loads that cause misalignment and envelope discontinuities, increasing the likelihood of air leakage and moisture deposition that can later manifest as durability or mold issue (Valinejadshoubi et al., 2022). This makes sensor-enabled monitoring and documented chain-of-custody condition checks particularly salient for prefabricated modules during transport, staging, and installation, especially when modules are factory-finished and time-to-assemble is compressed, undetected moisture accumulation can remain concealed within closed assemblies and compromise structural integrity and occupant health (Menneer et al., 2022).

Despite these advantages, implementation costs and operational complexity remain significant barriers, particularly for small and medium-sized enterprises (SMEs). Moreover, internet-enabled sensors raise specific concerns about cybersecurity, competitive transparency, and individual privacy. Addressing these issues requires robust governance frameworks for secure data sharing, standardized communication protocols, and participatory system design (Ingemarsdotter et al., 2020; Shennib et al., 2024).

4.4. Computer Vision for Quality and Traceability

CV technologies employ machine learning and image-recognition algorithms to automate defect detection, reduce rework, and improve assembly accuracy (Koulalis et al., 2022). They can also create verifiable visual records, which support material traceability from production through reuse or recycling (Panahi et al., 2024; Zocco et al., 2022). While CV strengthens quality assurance and circular tracking, its deployment may displace certain human roles. To promote adoption and social acceptance, CV should be implemented as a complement to skilled labor, enhancing human oversight and building trust rather than undermining workforce participation (Schmitt, 2024).

4.5. Blockchain for Certification and Secure Data

Blockchain provides decentralized, tamper-resistant systems for verifying compliance with reuse standards and certifying ownership and provenance across construction supply chains (Jiang et al., 2023; Li et al., 2022). By ensuring immutable records and transparent transactions, blockchain can strengthen traceability and reinforce CE-aligned practices such as component reuse and material passports. However, the value of blockchain depends on robust, standardized frameworks for interoperability and data governance (Awan and Sroufe, 2022; Çimen, 2021). Without these safeguards, blockchain systems risk fragmentation, high energy consumption, and inequitable outcomes.

4.6. Beyond Technology: Enabling Conditions

Collectively, BIM, IoT-enabled sensors, CV, and blockchain hold significant potential to transform construction by enabling continuous lifecycle management and advancing CE objectives. Yet their benefits are not guaranteed. Empirical evidence shows that effective circular systems can succeed without advanced technologies, relying instead on trust, cultural readiness, established logistics, and supportive infrastructure

(Brandão and Verissimo, 2024; MacKenbach et al., 2020; Nußholz et al., 2020). Over-reliance on digital tools, without these foundational conditions, risks reinforcing inequalities and undermining CE goals (Yu et al., 2025). Consequently, digital innovation should be understood as an accelerator rather than a prerequisite for CE–MOC, with its effectiveness contingent on inclusive governance, equitable access, and robust institutional and regulatory frameworks.

5. Circular Strategies in Modular Construction

MOC, with its off-site fabrication, controlled precision, and minimized on-site waste, can reduce environmental impacts compared with conventional construction methods. When combined with CE principles, MOC's potential may be amplified, becoming a structured pathway for closed-loop resource management and long-term sustainability in the built environment (Wuni and Shen, 2022; Zhuang et al., 2023).

5.1. Design for Disassembly and Material Reuse

At the core of CE–MOC integration is the capability to retain material value through reuse, refurbishment, and recycling. Drawing on the “9R” hierarchy (Andrews, 2015; Kirchherr et al., 2017; Merli et al., 2018; Santos et al., 2025), modular components can be designed for disassembly, reused across multiple projects, or remanufactured into new applications. Practical applications include selecting recycled inputs, incorporating sustainably sourced materials, and processing C&D waste into secondary raw materials to reduce landfill and embodied energy (Eberhardt et al., 2019; Odenbreit et al., 2023). Together, these strategies extend component lifespans and directly connect MOC workflows to CE objectives.

5.2. MOC Limitations & Trade-offs

While MOC is often presented as naturally compatible with CE principles, this alignment is not automatic and is constrained by design and operational trade-offs. Many modular systems prioritize speed, standardization, and cost efficiency over disassembly and material recovery, which can limit reuse pathways and complicate component separation (MacKenbach et al., 2020). In some cases, standardized module dimensions and composite material specifications may increase transportation intensity or reduce recyclability compared with non-modular alternatives (Ly et al., 2024; Shooshtarian et al., 2025). Without explicit CE-oriented design protocols and recovery strategies, modular construction risks reproducing linear material flows despite efficiency gains.

5.3. Economic and Regulatory Hurdles

Economic feasibility remains a major obstacle. Infrastructure for disassembly, remanufacturing, and certification requires substantial upfront investment in specialized equipment, workforce training, and quality-assurance protocols, costs that are often prohibitive for SMEs. Although the long-term savings from CE adoption can offset these expenses, such benefits frequently depend on policy instruments such as carbon pricing, full-cost accounting, or removal of environmentally harmful subsidies (García-Sánchez et al., 2021; Geissdoerfer et al., 2017; Miatto et al., 2024). Regulatory frameworks add further complexity. Building codes, procurement guidelines, and material standards frequently assume linear construction practices, thereby restricting the use of reused components and limiting the adoption of design-for-disassembly approaches (Duchin and Levine, 2019; Fonseca and Silva, 2023; Vergani et al., 2023). Enabling CE–MOC at scale will require proactive reforms, including certification systems for reclaimed components and updated codes that formally recognize modular reuse.

5.4. Systemic Benefits and Alignment with SDGs

Despite these challenges, embedding CE within MOC offers potential systemic benefits that are increasingly supported by empirical observations reported in MOC studies. Environmentally, lifecycle and comparative assessments indicate that MOC approaches can reduce construction waste generation, improve resource efficiency, and lower embodied carbon when circular strategies are incorporated into design and supply-chain

planning (Jayawardana et al., 2023a; Zhang et al., 2024; Ziaesaeidi and Noroozinejad Farsangi, 2024). These outcomes contribute to reducing dependence on virgin raw materials, lowering construction-related greenhouse gas emissions, and minimizing overall resource depletion (Nußholz et al., 2020; UCL et al., 2025).

Economically, CE-MOC integration can enhance supply-chain resilience, reduce long-term operating costs, and support business models based on refurbishment, remanufacturing, and resource recirculation (Ahmed et al., 2022; Ly et al., 2024; Sullcapuma Morales, 2023). Documented applications further suggest that modular production can improve scheduling predictability and reduce uncertainty compared with conventional site-based approaches, particularly when digital coordination and traceable material documentation are integrated into project delivery (Assaad et al., 2022a, 2022b; Jayawardana et al., 2025).

From a social perspective, CE-MOC has been associated with strengthening regional manufacturing networks, creating skilled employment opportunities, and improving occupational safety by shifting a large share of work toward controlled factory environments (Brandão and Verissimo, 2024; Chatzimichailidou and Ma, 2022; Zhuang et al., 2023). Case-based studies indicate that such environments may support safer working conditions and more stable employment structures compared with traditional construction settings, yet these outcomes rely on workforce training, organizational strategies, and institutional support (Assaad et al., 2022b; Jayawardana et al., 2023c; Sajid et al., 2024).

Taken together, the literature suggests that CE-MOC represents a promising pathway toward more regenerative construction systems, contingent on enabling design choices, verification mechanisms, and institutional alignment. This integration is also commonly linked to progress toward the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 on responsible consumption and production, SDG 13 on climate action, and SDG 8 on decent work and economic growth.

6. Social Dimensions and Equity Considerations

This section examines how social outcomes in CE-MOC systems are influenced by the design and use of digital platforms. These platforms increasingly support data sharing, monitoring technologies, and material traceability across construction actors. As a result, they can affect equity and workforce conditions in several ways: (i) access to shared digital data systems, which may create a digital divide that disadvantages SMEs, (ii) the use of sensing technologies, wearables, and computer vision to improve safety while also raising concerns about privacy and workplace surveillance, and (iii) trust mechanisms for reused materials, such as digital product passports and material passports that record provenance and condition. Within CE-MOC systems, these mechanisms influence how circular practices are perceived in reuse markets and whether workers experience technological changes as supportive or extractive (Brandão and Verissimo, 2024; Dainty et al., 2017; Honic et al., 2024; Jensen et al., 2023).

6.1. Workforce Development and Inclusion

CE-MOC integration is associated with creating employment opportunities in manufacturing, logistics, and digital operations that offer safer and more predictable working conditions than in traditional on-site construction, which generally carry greater risks due to its harsh and dynamically changing conditions as well as to exposure to extreme weather conditions (Almaskati et al., 2024; Supriyatna et al., 2020). For examples, safety modeling using national accident data in a New Zealand found onsite accidents occurring about four times more frequently than offsite work (Jayawardana et al., 2023b; Masood, 2024; Simukonda and Emuze, 2022). Localized supply chains help in enhancing resilience and inclusion by supporting small local businesses and in reducing transport-related emissions when they shorten factory-to-site distances and avoid cross-jurisdiction transport constraints (Arshad and Zayed, 2022; Popovic et al., 2018). In one comparative project-level LCA, prefabrication reduced GHG emissions from 281.56 to 258.86 kgCO₂e/m² (~8.06%) and distance sensitivity analysis identified an approximate ~340 km cut-off below which prefabrication still yielded GWP savings for a building with similar characteristics; beyond that distance, transport can erode or negate benefits, so impacts should be assessed case-by-case (Smith, 2016; Zaalouk et al., 2023).

MOC has been shown to reshape employment structures and working conditions compared with conventional on-site construction. Industry and policy analyses indicate that the expansion of modular construction is associated with a redistribution of labor toward factory-based manufacturing roles, with growing demand for skilled trades, digital fabrication, and production-oriented occupations as modular

markets scale (Bertram et al., 2019; Goulding et al., 2015; Truitt et al., 2023). Studies examining workforce implications of off-site construction further suggest that employment growth in manufacturing-style construction roles may partially offset declining demand for certain site-based activities, provided that reskilling and training pathways are available (Goulding et al., 2015; Walsh and Emery, 2022).

Beyond employment volume, modular manufacturing environments have been linked to improved workforce inclusion outcomes. Research on construction work environments shows that factory-based settings can reduce exposure to weather extremes, physical strain, and safety risks relative to traditional sites, contributing to improved job accessibility and retention (Hu et al., 2025; Jung et al., 2020; MEEA, 2024). Gender and diversity studies further report that traditional site-based culture can pose significant physical and psychosocial barriers for women and underrepresented groups, and that more structured, manufacturing-style environments and better-designed workplaces can help to lower some of these barriers (Boskovic et al., 2026; Campea, 2025; Yan et al., 2024). Additionally, MOC production initiatives have been used as platforms for structured training and apprenticeships by enabling repeatable processes, integration of digital tools and closer alignment between education providers and industry needs (Assaad et al., 2022b; Truitt et al., 2023; Walsh and Emery, 2022). However, the realization of these social and employment benefits is not automatic; the literature emphasizes that inclusive outcomes depend on deliberate workforce development strategies, collaboration with training institutions and unions, and facility design decisions that embed inclusion, safety, and skill progression into production systems (Galea et al., 2022; Lim and Loosemore, 2017; UN WEP, 2024).

Factory-based settings also foster greater workforce diversity. Unlike conventional construction sites, which often present physical and cultural barriers, modular environments reduce hazardous conditions and provide ergonomic workplaces. This enables broader participation from women, older workers, and those with physical limitations, aligning with the objectives of gender equality (SDG 5) and decent work and economic growth (SDG 8) (Berglund-Brown et al., 2022; Salles et al., 2024). Targeted upskilling initiatives and academic–industry partnerships can further expand pathways into sustainable construction careers, particularly for underrepresented groups and youth (Fan and Fan, 2024; Geissdoerfer et al., 2017).

6.2. Cultural Acceptance and Trust

Social acceptance is critical for scaling CE–MOC. Its adoption depends on confidence in reused materials, clear value propositions for stakeholders, and transparent governance frameworks (Jayawardana et al., 2023c; MacKenbach et al., 2020). Current barriers include fragmented interests among demolition contractors, designers, regulators, and reuse markets, as well as the absence of interoperable platforms to facilitate material exchanges (Zhuang et al., 2023). Evidence from pilot projects shows that without shared standards and demonstrated reliability, circular practices risk remaining conceptual ambitions rather than becoming mainstream solutions (Paquin et al., 2014).

At the same time, factory-controlled settings demonstrably can reduce certain occupational injury categories through elimination of fall hazards, ergonomic workstation design, and mechanized assembly. Studies such as (Hussain et al., 2024; Yang et al., 2017). Comparative research reports that approximately 60% of conventional construction incidents require medical aid compared with 35% in prefabrication facilities (Sharma et al., 2025), representing an approximate a 40% relative reduction in incidents requiring medical aid. This comparison aligns with broader safety analyses attributing differences to reduce hazard exposure, task standardization, and controlled work environments (Ahn et al., 2020; Yang et al., 2017).

Research examining workforce restructuring in MOC further indicates that factory-based production environments can reduce exposure to weather-related hazards, repetitive manual handling, and high-risk site activities through task standardization workflows and mechanized processes (Assaad et al., 2022b; Sajid et al., 2024). These findings provide measurable support for claims related to workforce safety and accessibility; however, the literature emphasizes that broader participation outcomes depend on deliberate workplace design, inclusive policies, and structured training pathways rather than being inherent outcomes of modularization itself (Assaad et al., 2022b; Jayawardana et al., 2023c).

6.3. Toward Socially Facilitated Circularity

Overall, the social dimension underscores that CE–MOC represents not merely a technical or economic transition but a relational transformation. Workforce development, inclusivity, and safety must be accompanied by cultural readiness, institutional trust, and equitable governance. Without these foundations, digital

innovation and material efficiency alone will not secure durable adoption. Embedding CE in MOC therefore requires parallel attention to social legitimacy, policy frameworks, and community engagement. The literature reviewed here indicates that workforce inclusion depends on structured training and workplace design, safety performance depends on hazard reconfiguration within controlled production environments, and material trust depends on transparent certification and traceable documentation systems.

7. Adoption Pathways and Governance

Mainstreaming CE-MOC requires interventions that move beyond isolated technological pilots toward coordinated, system-level implementation. As demonstrated across literature, technical capabilities alone are insufficient to enable circular outcomes unless they are embedded within certification regimes, regulatory recognition, and collaborative governance structures (Corvellec et al., 2022; Kirchherr et al., 2017). The barriers identified in earlier sections can therefore be addressed only through integrated pathways that align digital infrastructures with institutional and market mechanisms. The following subsections outline how certification and standardization, policy instruments, and multi-stakeholder governance collectively provide actionable pathways for CE-MOC, while acknowledging that most applications remain emergent and under active testing rather than fully institutionalized.

7.1. Certification and Standardization

Certification and standardization play a foundational role in enabling CE-MOC by legitimizing reused components and reducing perceived technical and legal risks (Adams et al., 2017; Ghisellini et al., 2016). Existing certification systems such as Cradle to Cradle (C2C) and Leadership in Energy and Environmental Design (LEED) provide high-level sustainability benchmarks and market signaling functions, but their application to modular reuse remains limited without project-level verification mechanisms that confirm material condition, performance, and traceability (Munaro and Tavares, 2021).

In practice, emerging CE-MOC applications increasingly rely on digitally supported documentation frameworks, such as BIM-linked inventories and Material Passports, to operationalize certification requirements across lifecycle stages (Kovacic et al., 2020; Liu et al., 2021). Sector-specific standards, including those governing reclaimed materials (e.g., SCI P427 and P440 in the context of structural steel) (Brown and L A Dougherty, 2023; Brown et al., 2019), illustrate how regulatory protocols define testing and verification requirements; however, these standards function as regulatory references rather than digital tools and require complementary digital systems to enable scalable implementation (Chiappetta Jabbour et al., 2020; Pedroso et al., 2024). In operational terms, such requirements are commonly enacted through structured digital records that link inspection results, test certificates, and chain-of-custody documentation to component identifiers within project information systems, using centralized databases, interoperable BIM-linked repositories, or permissioned blockchain-based ledgers for controlled data sharing, enabling auditability across design, procurement, and recovery stages (Byers et al., 2024; Shojaei and Naderi, 2024).

Digital platforms such as Madaster exemplify how material registries and passports can support certification processes by storing component attributes, testing records, and ownership histories in structured digital environments (Honic et al., 2024). While such platforms demonstrate technical feasibility, their adoption in CE-MOC remains largely limited to pilot projects and early adopters, underscoring the need for further validation and institutional alignment.

7.2. Policy Instruments and Regulatory Reform

Policy frameworks strongly influence whether certified reuse pathways are recognized and scaled. Effective CE-MOC adoption requires regulatory environments that permit reused components when equivalence to new materials can be demonstrated through documented testing and traceability (Kirchherr et al., 2023). At present, many building codes and procurement policies still embed a new-product equivalence logic that increases the evidentiary burden for reused components. For example, International Existing Building Code administrative provisions require reused materials to meet requirements for new materials (IEBC, 2025), similarly, the Ontario Building Code permits the reuse of building components provided that they comply with the requirements

applicable to new materials and are considered satisfactory for their intended structural and functional use (Ministry of Municipal Affairs and Housing, 2025).

In parallel reuse markets can be constrained when salvaged components are treated as waste unless they meet end-of-waste criteria under the EU Waste Framework Directive, 2008 as amended by Directive (EU) 2018/851 and Directive (EU) 2025/1892 (EU, 2025, 2018, 2008) or satisfy regulator guidance on reuse and end-of-waste status (e.g., UK Environment Agency frameworks and the CL:AIRE Definition of Waste Code of Practice) (Willenbrock, 2019), underscoring a practical reform pathway: clearer end-of-waste protocols coupled with standardized traceability documentation, such as through the revised EU Construction Products Regulation's Digital Product Passport direction (EU, 2025; Rockström et al., 2024; Stahel, 2016).

Digital technologies such as BIM-based compliance documentation, CV for component identification, and IoT-enabled monitoring can support regulatory reform by providing verifiable evidence of material condition and lifecycle performance (Sumter et al., 2021). However, these technologies are not policy solutions in themselves. Their effectiveness depends on governance frameworks that define data ownership, interoperability requirements, and responsibilities among designers, certifiers, contractors, and regulators (Mäkitie et al., 2023; Yu et al., 2025). Consequently, policy instruments must evolve in parallel with digital infrastructures to ensure that verified reuse is institutionally recognized rather than treated as an exception.

7.3. Collaborative Governance and Multi-Stakeholder Engagement

Transformative CE-MOC adoption depends on collaborative governance that aligns technical systems with institutional roles and stakeholder incentives. Public-private partnerships and academic-industry collaborations have been identified as critical mechanisms for testing reuse pathways, developing shared standards, and building professional capacity (de Oliveira and Oliveira, 2023; Mhatre et al., 2021). At the same time, demand-side engagement through labeling schemes and transparency mechanisms can strengthen market confidence in reused modular components (Alite et al., 2023).

Lessons from other sectors illustrate how cross-organizational coordination supports circular implementation. For example, the automotive sector demonstrates the value of design-for-disassembly and reuse in closing the CE loop, with companies like BMW and Tesla partnering with other firms to prioritize battery reuse in second-life stationary energy storage applications (Chiappetta Jabbour et al., 2020; Kristensen and Mosgaard, 2020). The electronics industry highlights take-back schemes and IoT-enabled tracking as tools for lifecycle extension (Banihashemi et al., 2024). Renewable energy deployment shows how subsidies and tax incentives can accelerate sustainable transitions, while pharmaceutical and biotechnology sectors showcase regulatory agility and public-private collaboration (Azhar et al., 2013; de Oliveira and Oliveira, 2023). While these models are not directly transferable, they provide relevant governance analogies for CE-MOC, where material passport platforms, shared BIM environments, and certification records can facilitate coordination between manufacturers, deconstruction contractors, reuse operators, and regulators.

In the construction context, such arrangements remain largely experimental, with most documented applications confined to demonstrator projects rather than routine practice. This reinforces the importance of governance structures that support learning, adaptation, and trust-building alongside technical deployment.

7.4. Pathways to Unlocking CE-MOC

The integration of CE within MOC progresses most effectively when strategies, barriers, and enabling conditions are explicitly linked to operational workflows rather than treated as abstract principles. Figure 3 synthesizes these interconnections by illustrating how CE principles can be supported across modular construction phases through digital inventories, material passport systems, certification standards, and policy recognition, all embedded within collaborative governance structures.

The pathway provided in this research builds on and extends prior CE-MOC research by clarifying how these elements interact across lifecycle stages, translating governance-oriented insights into an implementation-oriented roadmap (Gharib and Moselhi, 2025). Rather than presenting CE-MOC as an established solution, the framework provides a structured roadmap for aligning digital platforms, certification regimes, and governance mechanisms as they continue to be tested and refined in practice. In doing so, it supports a transition from isolated pilot initiatives toward more coordinated, evidence-informed approaches to circular construction, aligned with broader sustainability objectives and the Sustainable Development Goals.



Figure 3. Implementation Framework: How Digital Platforms Enable Circular Economy-Modular Construction Integration. The framework illustrates how specific digital technologies (BIM for lifecycle data integration, blockchain for certification, IoT-sensors for monitoring, CV for quality assurance) operationalize CE principles across each MOC phase (design, manufacturing, assembly, use-phase, recovery), supported by enabling conditions (certification standards, supportive policy, collaborative governance) aligned with UN SDGs.

8. Discussion

CE principles and MOC are frequently presented as mutually reinforcing approaches to sustainable construction. However, the literature synthesized in this research demonstrates that their alignment is neither automatic nor universal. While modular systems can reduce certain forms of waste and improve production efficiency, circular outcomes depend on whether reuse pathways, design-for-disassembly, certification mechanisms, and market acceptance are intentionally embedded. Many modular systems remain optimized for speed, cost, or performance, relying on composite materials and logistics configurations that complicate reuse and may introduce additional environmental burdens, particularly through transportation intensity and limited material recoverability (Ly et al., 2024; MacKenbach et al., 2020; Nußholz et al., 2020). These findings reinforce the need to frame CE–MOC integration as a socio-technical and governance-dependent challenge rather than an inherent design advantage.

A central contribution of this research lies in clarifying the role of digital platforms in operationalizing CE–MOC. Rather than treating BIM, IoT-enabled sensors, CV, and blockchain as a single technological solution, the analysis conceptualizes them as interdependent platform components whose value emerges through integration, interoperability, and governance. Across the reviewed literature, digital tools support traceability, quality assurance, lifecycle documentation, and reuse decision-making, but these outcomes are not ensured by digitization alone. Traceability, for example, depends on data completeness, verification practices, stakeholder compliance, and the institutional legitimacy of certification and data-sharing standards (Bartlett et al., 2020; Dou et al., 2024; Sumter et al., 2021). This distinction directly addresses earlier assumptions in CE–MOC research that digitalization inherently guarantees circular performance.

The findings further show that governance conditions shape the effectiveness of digital platforms more than technical capability alone. Without interoperable standards, clear data ownership arrangements, and equitable access, platform-based systems risk reinforcing existing market asymmetries and excluding small and medium-sized enterprises from circular supply chains (Ingemarsdotter et al., 2020; Mäkitie et al., 2023; Yu et al., 2025). At the same time, documented reuse systems demonstrate that circular practices can function effectively without advanced digital infrastructure when supported by trust, cultural readiness, and established institutional arrangements (Brandão and Verissimo, 2024; Paquin et al., 2014). These observations support the interpretation of digital platforms as accelerators of CE–MOC rather than prerequisites for circularity.

From an implementation perspective, the synthesis suggests that organizations operating in modular construction and adjacent supply chains should prioritize decision-grade lifecycle information over the isolated adoption of digital tools. The framework emerging from this review points toward coordinated application of digital platforms with certification systems, performance-based reuse pathways, and transparent governance mechanisms. Such an approach enables firms to collaborate across organizational and sectoral boundaries, share verified material data, and reduce uncertainty associated with reused components, rather than relying solely on proprietary or project-specific solutions (Kirchherr et al., 2023; Ly et al., 2024; Munaro and Tavares, 2021).

For policymakers, governments should update building regulations so reused components meet safety standards (e.g. allow salvaged beams in new projects) and mandate design-for-disassembly (Luoma-aho et al., 2024). Public procurement and subsidies can create demand (e.g. require a percentage of reused materials in public buildings) (Heisel et al., 2024). Digital platforms (material passports, BIM) should be funded or required to track and match reusable materials (Ammari and Guerriero, 2026; De Wolf, 2022). Pilot projects must tie directly to policy: evaluate CE construction pilots and quickly codify successful practices into guidelines (Ansell and Bartenberger, 2025). Finally, invest in training and networks (curricula, expert forums) so industry knows how to implement these practices (Ansell and Bartenberger, 2025; Muriithi and Ngare, 2023).

Finally, this research contributes to CE–MOC scholarship by moving beyond descriptive alignment toward an implementation-oriented understanding of how circular construction systems can function in practice. By explicitly linking digital platforms, governance mechanisms, and social conditions, the discussion reframes CE–MOC not as a self-evident technological progression but as a transition contingent on coordinated design, institutional alignment, and responsible digital integration. As this review is based on synthesized evidence rather than empirical field studies, future research should prioritize pilot applications, longitudinal evaluations, and cross-regional comparisons to test platform-enabled CE–MOC under real-world constraints and to examine trade-offs related to digital infrastructure impacts and labor dynamics (Corvellec et al., 2022; Yu et al., 2025).

9. Summary and Concluding Remarks

This research examined how CE principles can be operationalized within MOC, with particular attention to the enabling role of digital platforms. The review shows that digital tools such as BIM, IoT-enabled sensors, CV, and blockchain can support lifecycle traceability, verifiable provenance, and material reuse. At the same time, the analysis demonstrates that circular outcomes are not delivered by technology alone. The success of CE–MOC depends fundamentally on governance structures, certification mechanisms, and inclusive stakeholder engagement that align environmental objectives with social and economic incentives.

A central contribution of this work is the articulation of a structured roadmap for applying CE principles in construction. The findings indicate that CE–MOC implementation requires a layered set of enablers. At the foundation, governance and institutional conditions are critical, including standardized certification for reused components, clear allocation of data ownership, and regulatory recognition of design-for-disassembly and reuse pathways. Building on this foundation, digital platforms can function as operational enablers by integrating lifecycle data, supporting verification and traceability, and coordinating actors across design, manufacturing, use, and recovery phases. Importantly, social enablers, including workforce development, trust in reused materials, and cultural acceptance, remain essential to ensure that circular strategies are adopted and sustained in practice.

From a practice perspective, the findings indicate that organizations seeking to implement CE–MOC should prioritize decision-grade lifecycle information and verified reuse pathways rather than focusing on individual digital tools. Effective implementation depends on combining digital integration with transparent certification processes, collaborative governance arrangements, and attention to local market and workforce conditions. This approach supports coordination across supply chains and, where relevant, collaboration with actors beyond the construction sector to enable reuse, refurbishment, and material recovery while reducing uncertainty and risk.

For policymakers, the analysis highlights the importance of enabling environments rather than prescriptive technology mandates. Supportive regulation, public procurement criteria that recognize circular performance, financial instruments that reduce risk for reuse and refurbishment, and interoperable certification frameworks can facilitate broader adoption of CE–MOC practices. These instruments are particularly important for lowering barriers faced by small and medium-sized enterprises and for translating pilot initiatives into scalable systems.

For research, this research highlights the need for empirical validation of CE–MOC propositions. Future work should focus on pilot projects, longitudinal assessments, and cross-regional comparisons to examine how integrated digital platforms perform under real-world constraints. Particular attention is needed to assess trade-offs associated with digital infrastructure impacts, labor dynamics, and the distribution of social and environmental benefits across contexts. Such evidence is necessary to refine CE–MOC approaches and to inform both practice and policy with greater precision.

Overall, this paper positions CE–MOC not as a guaranteed outcome of modularization or digitalization, but as a governance-dependent transition. By connecting circular strategies, digital platforms, and social considerations within coherent roadmap, the research contributes an implementation-oriented perspective on how construction systems can move toward more regenerative, resilient, and socially inclusive models of resource use.

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Declarations

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