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Validation of a Digital Framework for Circular Economy Retrofits: A Multi-Case Analysis

Farokh Panahirad

PhD Student, Art University of Isfahan, Faculty of Architecture and Urban Design, Isfahan, Iran
F.Panahirad@aui.ac.ir

Abstract

Integrating Circular Economy principles into existing building retrofits offers substantial opportunities to reduce resource waste and improve operational efficiencies. This paper presents a multi-case analysis of eight retrofit projects—spanning offices, residential complexes, and historical structures—to validate a digital integration framework that leverages Building Information Modeling, the Internet of Things, Artificial Intelligence, and Digital Twins. Our analysis demonstrates that retrofits employing this framework can achieve material reuse rates between 40% and 80% and energy savings from 15% to 70%. In addition to quantifying performance improvements, the study examines challenges such as stakeholder resistance, data fragmentation, and regulatory constraints, and discusses strategies for effective framework implementation. The findings offer a robust roadmap for scaling digital-driven CE retrofits in the built environment.

Key words: Circular Economy, Building Retrofit, BIM, IoT, Material Reuse

1. Introduction

The built environment is one of the largest consumers of energy globally and is responsible for a significant share of greenhouse gas emissions [1, 2]. Traditionally, construction has followed a linear model—extract, build, use, and dispose—resulting in high levels of waste and resource depletion. In response to these challenges, the Circular Economy (CE) paradigm has gained traction as an alternative model that emphasizes waste minimization, resource recovery, and the extension of material lifespans [3–5]. CE approaches aim to close the loop by designing processes that enable the continuous reuse of resources, thereby reducing environmental impact and promoting sustainability.

While new construction projects have increasingly incorporated CE strategies, existing buildings—representing the majority of the built stock—present unique challenges for retrofitting. These structures are characterized by heterogeneous construction methods, outdated designs, and various regulatory and technical obstacles [6, 7]. Retrofitting such buildings requires careful consideration of material deterioration, heritage preservation, and occupant disruption. Consequently, effective CE retrofitting necessitates not only innovative design but also advanced technological solutions.

Digital technologies have emerged as critical enablers in addressing these retrofit challenges. Tools such as Building Information Modeling (BIM), the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins facilitate detailed data collection, real-time monitoring, and predictive analysis, thereby improving decision-making and operational performance [8–10]. These digital solutions enable precise documentation of as-built conditions, simulation of retrofit scenarios, and continuous performance optimization after project completion.

Despite the theoretical promise of these digital technologies, empirical validation of integrated frameworks remains limited. This study addresses that gap by evaluating a comprehensive digital integration framework for CE retrofits through a multi-case analysis. The framework is structured into four phases—Assessment, Planning, Execution, and Monitoring & Optimization—and is applied to eight diverse retrofit projects. The objective is to assess the framework's performance, quantify its benefits in terms of material reuse and energy savings, and identify persistent challenges that may hinder broader adoption.

2. Methodology

2.1 Research Design

A multi-case study approach was employed to evaluate the digital framework in a range of real-world retrofit projects. This design allowed for the collection of both qualitative and quantitative performance metrics across varied building typologies, thereby providing a comprehensive evaluation of the framework's effectiveness [11, 12]. By comparing outcomes across multiple cases, the study identified recurring themes and validated the robustness of the framework under different conditions.

2.2 Case Selection

Eight retrofit projects were selected based on the following criteria:

- **Diversity of Building Types:** The sample includes commercial offices, residential buildings, and historical structures. This diversity ensures that the framework is tested under various scenarios and that the findings are broadly applicable [13, 14].
- **Digital Tool Implementation:** Each project integrated at least two digital solutions (e.g., a combination of BIM with IoT or Digital Twins) to support CE outcomes. This criterion guarantees that the framework is applied in a sufficiently digitalized context.
- **Data Availability:** Selected projects provided robust quantitative data (e.g., energy consumption, material reuse rates) as well as qualitative insights (e.g., stakeholder satisfaction, regulatory challenges). This comprehensive data set allowed for detailed comparative analysis.

2.3 Data Collection and Analysis

Data collection was carried out using a triangulation of methods:

- **Document Review:** Academic publications, industry reports, and official project documentation were analyzed to extract relevant performance data and qualitative insights.
- **Performance Metrics:** Quantitative data were gathered on key indicators such as energy savings, material reuse, and waste reduction.
- **Comparative Synthesis:** Data were aggregated into summary tables and charts to identify cross-case trends and validate the effectiveness of each phase of the digital framework [11].

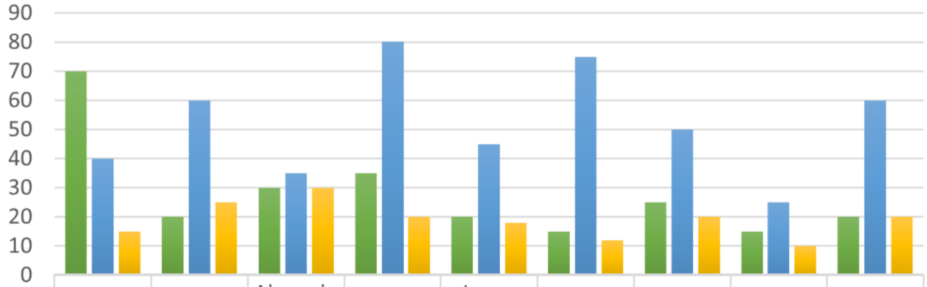
The use of multiple data sources enhanced the validity of the findings and provided a robust basis for analysis.

3. Case Studies and Comparative Analysis

This section provides a detailed overview of the eight retrofit projects analyzed in this study. Table 1 below summarizes the key characteristics, including building type, digital technologies employed, CE outcomes, and encountered challenges.

Table 1. Comparative Analysis of Retrofit Case Studies

Case Study	Building Type	Technologies Used	Key Outcomes	Challenges	Metrics
The Edge Building, Amsterdam **[8]**	Commercial Office	BIM, IoT, Digital Twins	70% energy savings, enhanced occupancy comfort	Minimal significant challenges	Energy Savings: 70%
Circular House Project, Denmark **[6]**	Residential Apartments	BIM	60% material reuse, 25% carbon reduction	Stakeholder engagement	Material Reuse: 60%, Carbon Reduction: 25%
Adaptive Reuse in The Netherlands **[14]**	Historical Buildings	BIM, IoT	80% heritage material conservation	Regulatory constraints	Material Conservation: 80%, Energy Improvement: 35%
Large Commercial Complex, Europe **[15]**	Commercial Complex	BIM, Digital Twins, IoT	45% waste reduction, 20% energy savings	Data integration challenges	Waste Reduction: 45%, Energy Savings: 20%
Urban Historical Area, Europe **[16]**	Historical Residential	BIM, Digital Twins	75% material preservation, 15% energy savings	Regulatory restrictions	Material Preservation: 75%, Energy Savings: 15%
Mixed-Use AECO Buildings **[8]**	Mixed-Use (AECO Sector)	BIM, Digital Twins	35% resource waste reduction	Operational scheduling	Resource Waste Reduction: 35%
Historic Public Building, Sweden **[10]**	Public Historic Building	Digital Twins, AI	20% energy reduction	Regulatory restrictions	Energy Reduction: 20%, Prediction Accuracy: 85%



	The Edge Building, Amsterdam	Circular House Project, Denmark	Alpnach, Switzerland (Mixed-Use Building)	Adaptive Reuse (Netherlands)	Large Commercial Complexes, Europe	Urban Historical Area, Europe	Mixed-Use AECO Buildings	Smartphone Reuse in Automation	Historic Public Building, Sweden
Energy Savings	70	20	30	35	20	15	25	15	20
Material Reuse	40	60	35	80	45	75	50	25	60
Carbon Reduction	15	25	30	20	18	12	20	10	20

Figure 1: Case study performance comparison chart

3.1 Material Reuse and Waste Reduction

Material reuse is a key indicator of CE performance. In the analyzed projects, reuse rates varied from 40% to 80%. Early-phase BIM audits facilitated the precise identification and documentation of salvageable components, particularly in heritage buildings where preserving culturally significant materials is critical [6, 14]. Additionally, strategic deconstruction enabled targeted salvage operations, leading to waste reduction levels ranging between 20% and 45% compared to conventional demolition techniques [9]. These findings indicate that a detailed digital assessment can substantially improve the recovery of materials, thereby reducing the overall waste generated during retrofit projects.

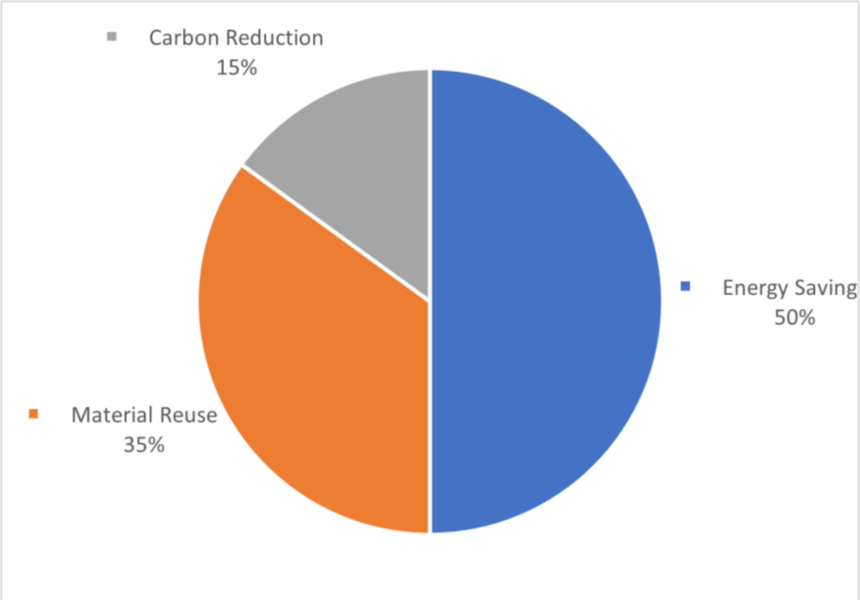


Figure 2: Impact metrics overview chart

3.2 Energy Savings

Energy savings represent one of the most significant benefits of retrofitting. Documented improvements ranged from 15% to 70%. In projects such as The Edge in Amsterdam, real-time IoT monitoring combined with AI-based optimization algorithms enabled continuous adjustment of building systems (e.g., HVAC, lighting) in response to occupancy patterns and environmental conditions [8, 10]. This dynamic adjustment resulted in substantial energy savings and improved indoor environmental quality. The reported performance aligns with recent studies on smart building retrofits, which document similar ranges of energy efficiency improvements through the integration of digital technologies.

3.3 Stakeholder Engagement

Effective stakeholder engagement is critical for the success of retrofit projects. In this study, projects that utilized Virtual Reality (VR) and digital twin simulations reported enhanced communication among building owners, occupants, and regulatory authorities [20, 21]. These tools provided stakeholders with a clear visualization of proposed interventions, enabling more informed decision-making and expediting regulatory approvals. Enhanced stakeholder engagement not only improves project buy-in but also minimizes resistance during implementation, leading to smoother and more efficient retrofits.

3.4 Data Integration Challenges

A recurring challenge observed across the projects was the fragmentation of data across multiple digital platforms. While some projects successfully implemented Common Data Environments (CDEs) to integrate data from BIM, IoT, and AI systems [22, 23], others—especially those executed by smaller firms—encountered significant interoperability issues [24]. These challenges underscore the need for standardized data protocols, such as those provided by the Industry Foundation Classes (IFC), to facilitate seamless data exchange and improve overall project performance [25]. Addressing these data integration issues is essential for enabling continuous performance monitoring and long-term optimization in retrofit projects.

4. Discussion

4.1 Validation of the Digital Framework

The proposed digital integration framework is organized into four distinct phases: Assessment, Planning, Execution, and Monitoring & Optimization. The multi-case analysis provides empirical evidence supporting the effectiveness of each phase:

- **Assessment Phase:**
  Projects such as The Edge and Historic Reuse employed detailed scan-to-BIM processes and digital twin development to comprehensively evaluate existing building conditions. This phase was critical for identifying salvageable materials, potential hazards, and areas requiring special attention, thus reducing unforeseen complications during execution [8, 13].
- **Planning Phase:**
  In the Planning phase, the integration of AI-driven scenario analysis and VR-based stakeholder consultations allowed project teams to simulate various retrofit strategies. For example, the Large Commercial Complex project used these tools to optimize retrofit strategies that maximized energy savings and material reuse while ensuring compliance with regulatory requirements [15, 20]. This phase enabled teams to select the most cost-effective and sustainable retrofit options.
- **Execution Phase:**
  During the Execution phase, real-time IoT monitoring was critical in allowing adaptive management. On-the-fly adjustments to demolition sequences and retrofit activities minimized material wastage and ensured that salvageable components were efficiently recovered. This proactive approach helped to reduce delays and cost overruns, as evidenced by the performance improvements documented in several projects [17].
- **Monitoring & Optimization Phase:**
  Finally, continuous data collection through IoT sensors and AI analytics in the Monitoring & Optimization phase enabled sustained performance improvements. Digital twins continued to play an important role by simulating future scenarios and enabling proactive maintenance decisions, thereby ensuring that energy efficiency and material conservation gains were maintained over the building's lifecycle [18].

4.2 Barriers and Enablers

The study identifies several barriers to the successful implementation of digital-driven CE retrofits, including:

- **High Upfront Costs:** Investments in BIM software, IoT sensors, and AI platforms are substantial, particularly for small organizations [4].
- **Regulatory Uncertainties:** Outdated or inconsistent regulatory frameworks can delay project approvals and increase project costs [7].
- **Data Interoperability Issues:** The lack of standardized data protocols often leads to fragmented information systems, impeding effective performance monitoring [24].
- **Skill Shortages:** A shortage of professionals trained in advanced digital techniques limits the full exploitation of these technologies.

Conversely, key enablers that support digital-driven CE retrofits include:

- **Phased Implementation:** Gradual investment in digital tools can help spread costs over time and reduce the initial financial burden [13].
- **Open Data Standards:** The adoption of open protocols, such as IFC standards, facilitates interoperability among digital systems and enhances data integration [22].
- **Comprehensive Training Programs:** Investing in cross-disciplinary training improves the skill base and enables more effective implementation of advanced digital technologies [24].

The empirical evidence from the case studies suggests that, despite these barriers, the environmental and economic benefits of digital-driven retrofits—such as significant energy savings and increased material reuse—justify the transition. These enablers not only mitigate the identified challenges but also create a conducive environment for the broader adoption of CE retrofits.

4.3 Implications for Practice and Policy

The findings of this study have important implications for both industry practice and policy development. For practitioners, the validated framework offers a structured roadmap for planning and executing CE retrofits. By following the four-phase approach, project teams can achieve substantial improvements in material reuse and energy efficiency while effectively managing risks associated with regulatory and technical challenges.

For policymakers, the study underscores the need for supportive measures to lower the barriers to adopting advanced digital technologies. Policy interventions such as tax incentives, subsidies, or green loans can help alleviate the financial burdens associated with high upfront costs. Moreover, the establishment of standardized data protocols and the promotion of industry-wide training programs are essential for facilitating the wider adoption of digital-driven retrofit practices. Such measures could accelerate the transition toward a more sustainable built environment and ensure that retrofit projects are both economically viable and environmentally beneficial.

4.4 Future Research Directions

While this study provides robust empirical validation of a digital framework for CE retrofits, several avenues for future research remain:

- **Long-Term Performance Evaluation:** Future studies should focus on post-occupancy evaluations and life-cycle cost analyses to assess the long-term benefits of digital-driven retrofits.
- **Standardized Data Protocols:** Research should aim to develop and refine standardized data protocols to enhance interoperability among digital tools, thereby reducing data fragmentation.
- **Scalability Studies:** Investigating the scalability of the digital framework in large building clusters or city-wide retrofit initiatives will help determine its broader applicability.
- **Emerging Technologies:** The potential impact of emerging technologies, such as blockchain for data security and advanced machine learning algorithms, warrants further exploration.
- **Comparative Analyses:** Comparative studies that evaluate digital-driven retrofits against traditional retrofit methods can help quantify the environmental and economic returns of adopting advanced digital technologies.

5. Conclusion

This study validates a comprehensive digital framework for Circular Economy retrofits through a multi-case analysis of eight diverse projects. The integration of BIM, IoT, AI, and Digital Twins facilitates significant material reuse (ranging from 40% to 80%) and energy savings (15% to 70%), while addressing persistent challenges such as stakeholder resistance, data fragmentation, and regulatory uncertainties. The four-phase framework—comprising Assessment, Planning, Execution, and Monitoring & Optimization—provides a structured approach that enables superior retrofit outcomes.

The empirical evidence presented extends existing literature by demonstrating that digital-driven CE retrofits are both environmentally and economically viable. The study highlights the importance of supportive policies, such as financial incentives and standardized data protocols, and emphasizes the need for comprehensive training programs to build the necessary skill base. Future research should focus on refining data integration and exploring the scalability of the framework to fully harness the potential of digital technologies in transforming the built environment.

In conclusion, the transition to digital-driven CE retrofits represents a critical step toward a more sustainable built environment. By leveraging advanced digital tools and adopting a phased implementation strategy, stakeholders can transform existing buildings into efficient, resource-conserving assets that contribute significantly to reducing the overall environmental impact of the construction sector.

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