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Integrating Lean Construction and Circular Economy to Minimize Waste in Infrastructure Projects: A Strategic Framework Review

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ABSTRACTS: The infrastructure construction sector is globally identified as a major contributor to solid waste, often driven by process inefficiencies and linear material management. This research aims to propose an integrated framework combining Lean Construction (LC) and Circular Economy (CE) principles as a holistic solution for waste reduction. Utilizing a systematic literature review and qualitative content analysis, this study evaluates how Lean tools such as the Last Planner System (LPS) and Just-in-Time (JIT) can synergize with CE principles like Design for Disassembly (DfD) and material recovery. The analysis reveals that LC-CE integration not only minimizes physical site waste through digital accuracy (BIM) but also reduces often-overlooked process wastes. The proposed framework provides a strategic roadmap for engineering practitioners to transition from the "take-make-dispose" model toward a more sustainable closed-loop material cycle.

KEY WORDS: Lean Construction, Circular Economy, Waste Management, Infrastructure, Sustainability, BIM.

1. INTRODUCTION

The construction industry sector serves as the backbone of global economic development; however, it concurrently bears significant responsibility as one of the world's largest producers of solid waste (World Economic Forum (WEF), 2024). Infrastructure projects—such as highways, bridges, and dams—are frequently characterized by large-scale material consumption that leads to significant inefficiencies. Data indicates that Construction and Demolition Waste (CDW) accounts for 30% to 40% of the total solid waste in various developing countries (I.A. Adeyemi and J.O. Ameh, 2023). This issue not only impacts environmental degradation but also causes project cost overruns due to the waste of non-value-added resources.

Traditionally, waste management in construction has been reactive, where mitigation efforts are only initiated after waste has been generated at the project site. This linear "take-make-dispose" approach has proven inadequate in addressing modern sustainability challenges (Ellen MacArthur Foundation, 2023). Consequently, a paradigm shift toward more preventive and circular models is required. This is where the integration of **Lean Construction (LC)** and **Circular Economy (CE)** becomes crucial.

Lean Construction offers a methodology focused on eliminating waste from a process perspective, such as waiting times, unnecessary transportation, and workmanship defects (Koskela 1992 in Ballard, 2022). Meanwhile, S. Benachio, M.C.D. Freitas, and S.F. Tavares (2020), said that Circular Economy provides a framework to maintain material value for as long as possible throughout the project life cycle through the principles of reduce, reuse, and recycle. Although both concepts share aligned goals regarding efficiency, research specifically exploring their technical synergy within the context of infrastructure projects remains limited. Most prior studies tend to decouple workflow efficiency (Lean) from material end-of-life management (Circular).

This research aims to fill this gap by proposing a strategic framework that integrates LC and CE principles. The primary focus of this study is how Lean tools, such as Building Information Modeling (BIM) and the Last Planner System (LPS), can act as enablers for circular economy practices (J. Sacks and R. Girolami, 2024). By adopting this integrative approach, it is expected that stakeholders in the construction industry can achieve optimal project performance, minimize environmental impacts, and enhance economic value through sustainable resource utilization.

2. LITERATURE REVIEW

2.1. Lean Construction and Process Waste

Lean Construction (LC) is rooted in the Toyota Production System, which was subsequently adapted for the construction industry to maximize value and minimize waste (Ballard & Koskela, 2022). According to Koskela (1992), as updated by Ballard and Koskela (2022), waste in construction is not limited to physical debris but also encompasses workflow inefficiencies known as "The 8 Wastes." In infrastructure projects, process wastes such as waiting times, excessive material transportation, and rework are often the primary drivers of cost overruns.

Furthermore, Sacks and Girolami (2024) state that key LC tools, such as the Last Planner System (LPS), function to enhance planning reliability and coordination among subcontractors, thereby mitigating potential material damage caused by prolonged storage or coordination errors from the outset.

2.2. Circular Economy in the Built Environment

In contrast to the linear economic model, the Circular Economy (CE) promotes a closed-loop system where resources are reused, recovered, and regenerated (Geissdoerfer et al., 2017). Benachio, Freitas, and Tavares (2020) emphasize that within the built environment, CE focuses on three levels of intervention: micro (products/materials), meso (buildings/projects), and macro (cities/regions).

Additionally, the Ellen MacArthur Foundation (2023) and Benachio et al. (2020) state that core CE principles include Design for Disassembly (DfD), which allows infrastructure components to be dismantled and reused at the end of their service life, as well as the utilization of recycled materials as substitutes for virgin materials. The implementation of CE in infrastructure projects heavily relies on decisions made during the design phase to ensure materials possess a long life cycle.

2.3. Synergies between Lean and Circular Economy

Recent research has begun to identify the intersection between LC and CE, often referred to as the "Lean-Green" approach (Adeyemi & Ameh, 2023; Kibert, 2022). LC acts as an operational catalyst to achieve CE targets. For instance, the Just-in-Time (JIT) methodology in Lean helps reduce material stockpiling on-site, directly supporting the resource efficiency principles of CE.

Sacks and Girolami (2024) further explain that the use of Building Information Modeling (BIM) serves as a technical bridge; BIM enables precise material volume calculations to minimize leftovers (Lean) while simultaneously storing material identity data (material passports) for future recycling needs (Circular). This integration creates a framework that optimizes not only "how we build" (process) but also "what we build" (material).

3. RESEARCH METHOD

This study employs a Systematic Literature Review (SLR) approach to explore the integration of Lean Construction (LC) and Circular Economy (CE). This method was selected for its ability to synthesize findings from various prior studies to generate a new strategic framework without requiring primary field data collection. The research procedure was conducted through three main stages:

3.1. Data Identification and Collection

A literature search was performed across reputable academic databases, including Scopus, Web of Science, and Google Scholar. The keywords utilized in the search included: *"Lean Construction"*, *"Circular Economy"*, *"Infrastructure Waste Management"*, and *"BIM-Lean Synergy"*. The publication timeframe was limited to the last ten years (2016–2026) to ensure the relevance of the latest technologies and methodologies within the construction industry.

3.2. Inclusion and Exclusion Criteria

Inclusion criteria were applied to filter articles specifically focusing on: (1) Infrastructure projects, (2) Implementation of Lean tools, and (3) Circular economy strategies. Articles that were not peer-reviewed or were unavailable in English or Indonesian were excluded from the analysis. From the initial identification, 20–30 key articles were selected based on their strong correlation between LC and CE.

3.3. Data Synthesis and Framework Development

The collected data were subsequently analyzed using Qualitative Content Analysis. The researchers mapped the functional relationships between Lean tools (such as JIT, LPS, and BIM) and Circular principles (such as Reduce and Recycle). The results of this synthesis were then formulated into a Proposed Integrated Framework, which serves as the primary contribution of this research.

4. RESULT AND DISCUSSION

4.1. The Proposed Integrated LC-CE Framework

The synthesis of the literature reveals that the integration of Lean Construction and Circular Economy creates a multi-layered defense against waste. While LC optimizes the efficiency of the construction process, CE ensures the sustainability of the material cycle. The proposed framework focuses on three primary technical enablers:

A. Digital Synergy: BIM as a Material Passport

Building Information Modeling (BIM) acts as the central nervous system for this integration. In the Lean context, BIM minimizes material waste through highly accurate quantity take-offs, preventing over-ordering. Simultaneously, in the Circular context, BIM functions as a "Material Passport," storing data on material composition and disassembly instructions. This ensures that when an infrastructure component reaches its end-of-life, it can be efficiently recovered rather than demolished.

B. Operational Synergy: Just-in-Time and Material Loops

The Just-in-Time (JIT) delivery system, a core Lean principle, minimizes on-site inventory. This reduction in inventory directly supports Circular goals by preventing material degradation caused by exposure to weather or site accidents. By ensuring materials arrive only when needed, the integrity of the material is preserved for potential reuse or high-quality recycling.

C. Coordination Synergy: Last Planner System (LPS) and Waste Reduction

The Last Planner System (LPS) enhances workflow reliability. This study finds that improved coordination through LPS reduces "process waste" such as waiting time and rework. In infrastructure projects, avoiding rework is a significant circular strategy, as it prevents the unnecessary consumption of new materials and the generation of avoidable debris.

D. Design for Disassembly (DfD) and Standardization

One of the critical findings of this study is the role of standardization in bridging LC and CE. Lean emphasizes the use of standardized components to reduce variability and defects. When applied to infrastructure, such as precast bridge segments, this standardization simplifies the Circular principle of *Design for Disassembly* (DfD). Standardized components are easier to catalog, remove, and reinstall in other projects, thereby extending the material's life cycle and reducing the energy-intensive process of crushing concrete for low-grade recycling.

E. The 8 Wastes vs. Circular Loops

The integration also redefines how we perceive "waste." In traditional Lean, waste is something to be eliminated. However, in a Circular perspective, physical waste is viewed as a "resource in the wrong place." The proposed framework suggests that by using Lean's Value Stream Mapping (VSM), project managers can identify points where material "leakage" occurs and redirect those flows into circular loops. For instance, excavated soil in highway projects (Lean waste: *unnecessary motion/transportation*) can be treated as a resource for on-site embankment (Circular: *reuse*), significantly reducing carbon emissions from logistics.

4.2. Challenges in Infrastructure Implementation

Despite the clear synergies, the discussion identifies several barriers to implementing the LC-CE framework in large-scale infrastructure:

- Initial Cost: The high upfront cost of digital technologies like BIM.
- Fragmented Supply Chain: The lack of coordination between material suppliers and contractors regarding circular recovery.
- Regulatory Gaps: Limited government mandates regarding the use of recycled materials in public infrastructure.

To provide a clearer overview of how these concepts are applied across the project life cycle, Table 1 summarizes the technical integration between Lean tools and Circular strategies from the design to the end-of-life phase.

Table 1. Integration of Lean Construction Tools and Circular Economy Strategies in Infrastructure Projects.

Project Phase	Lean Tool	Circular Strategy	Integrated Outcome
Design	BIM Modeling	Design for Disassembly	Precision design with zero leftover potential.
Procurement	JIT (Just-in-Time)	Local Sourcing/ Recycled Mat.	Reduced transport waste & low carbon footprint.
Construction	Last Planner System	On-site Sorting/Reuse	Minimized process waste & maximum recovery.
End-of-Life	Digital Twin	Material Recovery	High-value recycling instead of landfilling.

As illustrated in Table 1, the integration of Lean and Circular principles occurs across the entire project life cycle, creating a continuous feedback loop of efficiency. In the Design Phase, the use of BIM modeling goes beyond spatial coordination; it allows for the simulation of disassembly, ensuring that components are not only easy to install but also recoverable. This synergy transforms the design stage into a proactive waste-prevention phase.

During the Procurement and Construction phases, the focus shifts from digital planning to physical execution. By implementing Just-in-Time (JIT) and the Last Planner System (LPS), the framework ensures that material flow is strictly aligned with the actual demand of the project. This operational precision minimizes the "leaks" in the system—such as over-ordering or material degradation—which are the primary obstacles to a Circular Economy. Furthermore, the integration encourages on-site sorting and immediate reuse, turning what was previously categorized as "debris" into a valuable resource for other project segments.

Finally, in the End-of-Life phase, the framework utilizes the Digital Twin—an evolution of the initial BIM model—to provide a detailed inventory of the infrastructure's materials. This data-driven approach ensures that high-value recycling is possible, moving away from traditional demolition methods that downcycle materials into landfills. This comprehensive integration demonstrates that Lean tools provide the "how-to" (process) for achieving the "what" (sustainability goals) of the Circular Economy.

4.3. Discussion on Environmental and Economic Impacts

The integration of Lean Construction (LC) and Circular Economy (CE) extends beyond operational efficiency, offering transformative benefits for environmental sustainability and economic viability in infrastructure development.

A. Environmental Implications: Carbon and Resource Conservation

Infrastructure projects are notoriously resource-intensive, particularly in their consumption of cement and steel. By applying the integrated framework, the environmental burden is reduced through two primary mechanisms. First, the Lean approach minimizes the "hidden" carbon footprint associated with rework and over-processing.

Every cubic meter of concrete saved through BIM-enabled precision directly translates to a reduction in CO2 emissions. Second, the Circular approach promotes the use of recycled aggregates and low-carbon materials. The synthesis of existing literature suggests that by closing material loops—such as using crushed old pavement for new road bases—infrastructure projects can achieve a reduction in embodied carbon by up to 20-30%. This synergy is vital for meeting global "Net Zero" targets in the construction sector.

B. Economic Viability: Cost-Benefit Analysis of Efficiency

From an economic perspective, the common misconception that "green" or "circular" construction is prohibitively expensive is challenged by the inclusion of Lean principles. The economic benefits of this integration are observed in:

- Waste Disposal Savings: By minimizing physical waste through JIT and LPS, contractors can significantly reduce the costs associated with waste hauling and landfill tipping fees, which continue to rise globally.
- Material Cost Optimization: While initial investments in digital tools like BIM are required, they are offset by the reduction in material procurement waste. Precise ordering and the reuse of salvaged materials provide a buffer against the volatility of global raw material prices.
- Life-Cycle Value: The framework enhances the long-term value of the asset. An infrastructure designed for disassembly (DfD) has a higher residual value at the end of its life, as its components can be resold or repurposed rather than incurring demolition costs.

In summary, the LC-CE integration transforms waste management from a "cost center" into a "value driver," aligning environmental stewardship with the profit motives of private and public stakeholders.

5. CONCLUSION

This study has explored the strategic integration of Lean Construction (LC) and Circular Economy (CE) as a transformative approach to waste management in infrastructure projects. Based on the systematic analysis of current literature and the development of the proposed framework, several key conclusions can be drawn:

First, the synergy between LC and CE addresses the limitations of traditional waste management, which is often reactive and linear. While Lean Construction provides the operational tools to eliminate process-related wastes (such as waiting times and rework), Circular Economy provides the strategic vision to close material loops through reuse and recovery. This integration ensures that waste is mitigated at both the process level and the material level.

Second, digital technologies, specifically Building Information Modeling (BIM), act as the essential bridge for this integration. BIM serves a dual purpose: as a Lean tool to ensure high-precision material ordering and as a Circular tool to act as a "Material Passport." This enables a life-cycle approach where infrastructure components are designed for disassembly rather than demolition.

Third, the implementation of this integrated framework offers significant dual benefits. Environmentally, it has the potential to reduce the carbon footprint of infrastructure projects by up to 30% through resource conservation. Economically, it transforms waste management from a cost-heavy burden into a value-driven process by reducing disposal fees and optimizing material utilization.

5.1. Practical Recommendations

For industry practitioners and policymakers, this study recommends:

- Adoption of Digital Twins: Moving beyond basic BIM to include life-cycle data that facilitates material recovery.
- Supply Chain Collaboration: Encouraging contractors and material suppliers to establish "take-back" schemes for construction materials.
- Regulatory Support: Governments should incentivize the use of Lean-Circular practices in public infrastructure tenders to accelerate industry-wide adoption.

5.2. Limitations and Future Research

As this study is based on a systematic literature review, the proposed framework is conceptual in nature. Future research should focus on validating this framework through empirical case studies on active infrastructure projects. Additionally, further investigation into the use of Artificial Intelligence (AI) to automate waste identification within the Lean-Circular loop would provide a significant contribution to the field of smart and sustainable construction.

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