A Critical Review of Lean-BIM Synergies in Sustainable Pavement and Subsurface Systems

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Abstract

Subsurface infrastructure forms the structural backbone of sustainable pavement systems, yet it remains inadequately integrated within traditional road construction practices. Deficiencies in soil stabilization, drainage coordination, and lifecycle planning significantly compromise the durability and performance of Reinforced Cement Concrete (RCC) pavements. Lean Construction (LC) and Building Information Modelling (BIM) have emerged as transformative methodologies capable of addressing inefficiencies across the construction lifecycle. Lean emphasizes waste reduction and workflow stabilization, whereas BIM enhances visualization, information integration, and collaborative decision-making. Their integration referred to as Lean–BIM offers substantial potential for optimizing pavement and subsurface systems through improved coordination, reduced rework, and lifecycle sustainability.

This paper presents a structured critical review of existing literature on Lean, BIM, and their integration in infrastructure projects, with specific emphasis on pavement and subsurface systems. Recent advancements (2020–2024) are incorporated to reflect contemporary developments. The study identifies key research gaps, particularly the absence of RCC specific Lean–BIM frameworks and limited empirical validation in developing regions. The review concludes by proposing future directions for developing scalable, context-sensitive Lean–BIM integration models for sustainable RCC road infrastructure.

Keywords: Lean Construction, Building Information Modelling, Lean–BIM Integration, RCC Pavements, Subsurface Systems, Sustainability

1. Introduction

Sustainable pavement infrastructure depends fundamentally on the quality and coordination of subsurface systems, including subgrade preparation, drainage networks, and base stabilization layers. However, conventional road construction practices often treat subsurface and surface components independently, leading to fragmented planning, inadequate data integration, and premature pavement failures. Lean Construction, rooted in the production philosophy introduced by Lauri Koskela, promotes value maximization and systematic waste elimination. Simultaneously, Building Information Modelling, as conceptualized in the BIM framework developed by Chuck Eastman and colleagues, provides a digital platform for collaborative, data rich project management. The integration of Lean and BIM, systematically analyzed by Rafael Sacks and collaborators, demonstrates synergistic potential in improving information flow, reducing variability, and enhancing production control. Despite growing research, Lean–BIM integration remains predominantly building-focused, with limited exploration in pavement and subsurface systems. This review critically evaluates existing literature to assess how Lean–BIM synergies can enhance sustainability in RCC pavement infrastructure.

2. Subsurface Systems and Pavement Sustainability

2.1 Role of Subsurface Systems in RCC Pavements

The long-term structural performance of RCC pavements depends on:

- ✓ Proper subgrade compaction
- ✓ Adequate moisture control
- ✓ Effective drainage systems
- ✓ Accurate geotechnical data integration
- ✓ Failures in subsurface coordination result in cracking, faulting, pumping, and reduced service life.

2.2 Challenges in Current Practice

Literature identifies several recurring challenges:

- ✓ Limited geotechnical–design integration
- ✓ Incomplete subsurface data modelling
- ✓ Utility conflicts discovered during execution
- ✓ Minimal lifecycle-based drainage planning
- ✓ Poor coordination between design and field teams

These deficiencies highlight the need for integrated process and information management systems.

3. Lean Construction for Sustainable Pavement Development

3.1 Waste Reduction in Pavement Projects

Lean identifies seven classical wastes: overproduction, waiting, transportation, over-processing, motion, inventory, and defects. In RCC pavement works, these manifest as:

- ✓ Idle machinery during sequential activities
- ✓ Rework due to drainage misalignment
- ✓ Delays caused by poor material flow
- ✓ Underutilized labour during curing phases

3.2 Workflow Stabilization for Linear Infrastructure

Pavement construction is inherently linear and repetitive. Lean tools such as:

- ✓ 5s Methodology
- ✓ Last Planner System (LPS)
- ✓ Value Stream Mapping (VSM)
- ✓ Takt Planning
- ✓ Pull-based scheduling

improve coordination among excavation, compaction, reinforcement placement, and concrete casting operations.

3.3 5S Methodology in Pavement and Subsurface Works

The 5S methodology Sort, Set in Order, Shine, Standardize, and Sustain originates from Japanese production systems. It improves site organization and process discipline.

In RCC and subsurface works, 5S supports:

- ✓ Organized storage of reinforcement and drainage components
- ✓ Reduced material handling time
- ✓ Improved safety in excavation zones
- ✓ Standardized quality inspection procedures

✓ Sustained operational discipline across linear segments

When combined with BIM visualization, 5S can be digitally monitored to ensure site-wide compliance.

4. Building Information Modelling (BIM) for Pavement and Subsurface Systems

4.1 BIM Functionalities

BIM supports digital representation and coordination of pavement and subsurface components, offering:

- ✓ 3D modeling of pavement layers and utilities
- ✓ Clash detection for drainage and subsurface conflicts
- ✓ 4D sequencing of RCC construction processes
- ✓ Digital records of compaction, curing, and material testing

4.2 Geotechnical and Subsurface Integration

Recent work in geotechnical BIM integration emphasizes:

- ✓ Digital terrain modelling
- ✓ Drainage simulation
- ✓ Cross-sectional coordination
- ✓ Utility conflict resolution
- ✓ However, integration with Lean production control remains limited.

5. Lean–BIM Integration: Critical Review of Author Contributions

The foundational interaction matrix proposed by Rafael Sacks demonstrated 55 interaction points between Lean principles and BIM functionalities. While conceptually robust, empirical validation in pavement systems was limited.

Subsequent research by Algan Tezel identified implementation barriers including organizational resistance and fragmented supply chains.

Transportation focused BIM studies led by Aaron Costin emphasized interoperability challenges but did not deeply integrate Lean methodologies.

Recent sustainable pavement simulation research by Jian Zhang demonstrated BIM’s ability to reduce environmental impact, yet workflow optimization tools such as LPS were not incorporated.

Systematic reviews by Algan Tezel and collaborators indicate that most Lean–BIM integration studies remain concentrated in vertical construction, with minimal attention to RCC roads or subsurface coordination.

Critical Insight

- ✓ Lean studies emphasize process efficiency but underutilize digital modelling.
- ✓ BIM studies emphasize visualization but lack production control integration.
- ✓ Integrated Lean–BIM studies rarely address subsurface systems.
- ✓ RCC pavement specific frameworks remain absent.

Thus, theoretical synergy exists, but field level structured implementation models for pavement infrastructure are insufficient.

6. Recent Advances (2020–2024)

Recent research trends include:

- ✓ BIM-based pavement sustainability simulations
- ✓ Digital twins for infrastructure monitoring
- ✓ IoT-enabled compaction quality control
- ✓ Cloud-based Common Data Environments (CDE)
- ✓ AI-driven scheduling integrated with pull planning

These advancements indicate movement toward data-driven Lean–BIM ecosystems, yet standardized frameworks for RCC road infrastructure are still emerging.

7. Research Gap

The review identifies five critical gaps:

1. Limited subsurface-centric Lean–BIM frameworks
2. Absence of RCC pavement-specific integration models
3. Minimal empirical validation in Indian municipal projects
4. Weak lifecycle-based digital monitoring strategies
5. Lack of scalable implementation guidelines

Addressing these gaps requires a structured, context-sensitive Lean–BIM framework tailored to sustainable RCC pavement systems.

8. Future Research Directions

Future studies should focus on:

- ✓ Developing Lean–BIM frameworks specific to RCC pavements
- ✓ Integrating geotechnical digital twins into BIM workflows
- ✓ Standardizing Lean-based subsurface quality protocols
- ✓ Establishing municipal implementation guidelines
- ✓ Conducting empirical validation studies in developing regions

9. Conclusion

Subsurface systems are central to the durability and sustainability of RCC pavements but remain under-integrated in conventional construction practices. Lean Construction offers process optimization and waste reduction, while BIM enhances digital coordination and lifecycle visibility. Their integration presents transformative potential for sustainable pavement infrastructure.

Although literature confirms theoretical synergies, practical, scalable, RCC-specific Lean–BIM models are still lacking. Bridging this gap requires context-sensitive frameworks supported by empirical validation and digital lifecycle integration.

The advancement of Lean–BIM in sustainable pavement and subsurface systems therefore represents both a research necessity and an opportunity for infrastructure modernization.

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