Doctoral Dissertation
Doctoral Program in Civil and Environmental Engineering (38th Cycle)

Enhancing the Environmental, Social, and Economic Sustainability of Infrastructures: A Framework for Pavement Management

Rajab Ali Mehraban
……

Supervisor
Prof. Lucia Tsantilis

Co-supervisors
Prof. Pier Paolo Riviera
Prof. Ezio Santagata

Politecnico di Torino
October, 2025

Abstract

This research presents a novel, ISO-aligned sustainability assessment framework for asphalt mixture production and pavement rehabilitation strategies. The framework was developed and empirically tested to bridge the imbalance inherent in conventional sustainability assessments, which often emphasize environmental or economic aspects in isolation. By integrating environmental, social, and economic dimensions within a unified Life Cycle Sustainability Assessment (LCSA) structure, the study establishes a comprehensive pathway toward data-driven and balanced decision-making in pavement management. This approach represents a significant advancement toward achieving a more resilient, low-carbon, and socially responsible transportation infrastructure system.

A comprehensive review of existing Sustainability Rating Systems (SRSs), including CEEQUAL, Greenroads, GreenLITES, GreenPave, I-LAST, INVEST, BE2ST-in-Highways, and Envision, revealed a critical methodological gap. Most of these systems rely on qualitative, checklist-based indicators and lack integration among the environmental, social, and economic pillars of sustainability within a unified, quantitative framework. This limitation prevents a holistic trade-off analysis and constrains the ability to make data-driven comparisons across projects or regions, underscoring the need for a standardized Life Cycle Sustainability Assessment (LCSA) approach.

To address this deficiency, this dissertation develops a rigorous, quantitative, and ISO-compliant LCSA methodological framework tailored for asphalt pavement systems. The LCSA uniquely integrates Environmental-LCA (ISO 14040/44), Social-LCA (UNEP/SETAC and ISO 14075), and Life Cycle Costing (LCC) (ISO 15686-5) under a unified, consistent boundary extending from raw-material supply through to on-site construction (A1 to A5). This cohesive approach ensures direct transparency and comparability across all three sustainability dimensions, overcoming the siloed limitations of previous studies.

The framework relies on parameterized and transferable modules for asphalt mixture production (A1 to A3) and three common rehabilitation strategies: Full-Depth Reclamation (FDR) plus Overlay, Cold In-Place Recycling (CIR) plus Overlay, and conventional Mill and Overlay. These platform-independent modules were tested on case studies representing real-world rehabilitation projects with equivalent overall structural performance 2.26. Primary data were collected from rehabilitation projects in Virginia, U.S., providing granular information on fuel consumption and material use. Secondary data utilized robust sources, including the USLCI, Ecoinvent 3.9, SHDB 2024, and VDOT statewide cost averages 2025. All analyses were consistently anchored to a functional unit of one lane-mile.

The empirical results conclusively demonstrate the superiority of recycling-based strategies across all three pillars of sustainability (Environment, Social, and Economic). Environment-LCA results show that CIR-based strategy without using cement stabilizer achieves 35% lower Global Warming Potential (GWP) than conventional Mill and Overlay strategy, primarily due to reduced virgin-material extraction and lower energy demand. Asphalt mixture production (A1 to A3) consistently identified as the dominant environmental hotspot. The Social-LCA indicated that CIR scenarios exhibited a 60% lower social-risk intensity per lane-mile compared to conventional Mill & Overlay strategy, stemming from a reduced reliance on complex, high-risk global supply chains; improvements were most pronounced in worker health and safety. The LCC analysis confirmed CIR plus Foamed Asphalt plus HMA Overlay as the most cost-efficient option (USD 207,961 per lane-mile), being approximately 47% cheaper than the Mill and Overlay strategy

(USD 355,382). This confirmed that minimizing virgin-material use through recycling translates directly into combined economic and environmental benefits.

In conclusion, this study establishes a standardized and ISO-aligned LCSA framework that quantitatively integrates environmental, social, and economic sustainability for asphalt mixture production and pavement rehabilitation strategies. The developed modules are adaptable across platforms, provide a replicable foundation for future LCSA-based EPD and PCR initiatives and integration into Sustainability Rating Systems. By bridging methodological gaps and expanding life-cycle assessment beyond the gate, this research advances evidence-based, circular, and socially responsible for pavement management, supporting global efforts to build low-carbon and resilient transportation infrastructure.

Keywords: Sustainability Rating Systems, Life Cycle Sustainability Assessment, Environmental Life Cycle Assessment, Social Life Cycle Assessment, Life Cycle Costing, Pavement Management.