AFRICAN STRUCTURAL ENGINEERING

ORIGINAL RESEARCH

A Bayesian Hierarchical Model for the Efficiency Diagnostics of Municipal Infrastructure Asset Systems in Ethiopia

Tewodros Assefa[1] | **Meklit Gebrehiwot**[1]

1 *Addis Ababa University*

Correspondence: tassefa@outlook.com

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ABSTRACT

Municipal infrastructure asset systems in developing nations are often characterised by heterogeneous performance and limited data, challenging conventional efficiency evaluation methods that require large, uniform datasets. This study develops and validates a novel Bayesian hierarchical model to diagnose the operational efficiency of diverse municipal infrastructure systems, specifically addressing data scarcity and contextual variability. A cross-sectional dataset from multiple municipal jurisdictions was analysed using a Bayesian hierarchical model, $y\{ij\}\ sim\ text\{Normal\}(alphaj\ +\ \beta\ X\{ij\}, \sigma^2)$, $alphaj\ sim\ text\{Normal\}(\mu\{\alpha\}, \tau\{\alpha\}\text{^}2)$, where y_{ij} is an efficiency metric for asset i in jurisdiction j. Posterior distributions were estimated using Hamiltonian Monte Carlo, with inference based on 95% credible intervals. The model identified significant latent efficiency disparities between jurisdictions, with a posterior probability exceeding 0.95 that the efficiency coefficient for rehabilitated assets was between 1.15 and 1.30 times that of ageing assets. This indicates a clear, quantifiable performance gain from targeted renewal programmes. The Bayesian hierarchical framework provides a robust diagnostic tool for infrastructure efficiency under data constraints, successfully quantifying uncertainty and borrowing strength across groups to inform asset management. Municipal engineers and policymakers should adopt probabilistic, hierarchical modelling for asset system diagnostics to prioritise interventions. Future research should integrate temporal dimensions to model efficiency degradation. Infrastructure asset management, efficiency diagnostics, Bayesian hierarchical modelling, municipal engineering, probabilistic inference This paper presents a novel application of Bayesian hierarchical modelling to municipal infrastructure efficiency, providing a methodological framework that explicitly quantifies uncertainty for heterogeneous systems in data-scarce environments.

Keywords: *Bayesian hierarchical modelling, infrastructure asset management, efficiency diagnostics, Sub-Saharan Africa, municipal engineering, developing economies, performance evaluation*

Article Highlights

- Novel Bayesian model addresses data scarcity in developing economies.
- Quantifies latent efficiency disparities between municipal jurisdictions.
- Posterior probability >0.95 shows clear gain from asset renewal.
- Provides probabilistic framework for prioritising infrastructure interventions.

Key Finding

Rehabilitated assets demonstrated 1.15 to 1.30 times the efficiency coefficient of ageing assets, with posterior probability exceeding 0.95.

This study offers a methodological advance for infrastructure diagnostics where conventional data-rich approaches are impractical.