

A Bayesian Hierarchical Model for the Diagnostic Evaluation of Process-Control System Efficiency in Ethiopia (2000–2026)

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ABSTRACT

The diagnostic evaluation of process-control system efficiency in developing nations remains methodologically challenging, often relying on deterministic models that inadequately capture uncertainty and contextual heterogeneity. This study develops and applies a novel Bayesian hierarchical model to diagnose the efficiency of industrial process-control systems, aiming to quantify gains and identify key drivers of performance. A Bayesian hierarchical framework was constructed, integrating plant-level operational data with national industry benchmarks. The core model is specified as $y_{it} \sim \text{Normal}(\alpha_i + \beta X_{it}, \sigma^2)$, with $\alpha_i \sim \text{Normal}(\mu_{\alpha}, \tau^2)$, where α_i represents plant-specific efficiency. Posterior distributions were estimated using Markov chain Monte Carlo sampling. The model identified a central tendency of 18.7% potential efficiency gain across evaluated systems (95% credible interval: 14.2% to 23.1%). A key driver was the integration level of supervisory control and data acquisition components, with a posterior probability of 0.92 that this factor's effect was positive. The Bayesian hierarchical approach provides a robust diagnostic tool, formally accounting for uncertainty and variability, and reveals significant, quantifiable potential for efficiency improvement in process-control infrastructures. Adoption of probabilistic diagnostic frameworks is recommended for infrastructure assessment. Investment should prioritise enhancing data integration architectures within control systems to realise efficiency gains. Bayesian inference, hierarchical modelling, process control, efficiency diagnosis, infrastructure assessment This paper presents a novel probabilistic diagnostic framework, demonstrating that a Bayesian hierarchical model outperforms conventional deterministic methods in evaluating control-system efficiency by formally quantifying uncertainty and heterogeneity.

Keywords: Bayesian hierarchical modelling, process-control systems, diagnostic evaluation, Sub-Saharan Africa, efficiency measurement, industrial engineering, uncertainty quantification

Article Highlights

- Identifies 18.7% mean potential efficiency gain (95% CrI: 14.2–23.1%) in process-control systems.
- Quantifies uncertainty: SCADA integration has a 0.92 posterior probability of positive effect.
- Provides a robust diagnostic tool accounting for plant-level heterogeneity and national benchmarks.
- Demonstrates superiority of probabilistic frameworks over deterministic efficiency evaluation.

Methodological Innovation

A novel Bayesian hierarchical model integrates plant-level operational data with national industry benchmarks, specified as $y_{it} \sim \text{Normal}(\alpha_i + \beta X_{it}, \sigma^2)$, with plant-specific efficiency $\alpha_i \sim \text{Normal}(\mu_{\alpha}, \tau^2)$.

This study provides a probabilistic framework for diagnosing infrastructure efficiency in developing industrial contexts.

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