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CASE STUDY

A Bayesian Hierarchical Model for the Cost-Effectiveness of Process-Control Systems in South Africa

A Methodological Case Study

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ABSTRACT

Process-control systems are critical for infrastructure efficiency, yet rigorous, data-driven frameworks for evaluating their cost-effectiveness in engineering projects are lacking, particularly in resource-constrained environments. This case study presents a novel Bayesian hierarchical modelling framework to quantify the cost-effectiveness of process-control systems, aiming to provide a robust methodological tool for engineering decision-makers. A Bayesian hierarchical model was developed, formalised as $y\{ij\} sim text\{Normal\}(alphaj + \beta X\{ij\}, \sigma^2)$, $alphaj sim text\{Normal\}(\mu\{\alpha\}, \tau^2)$, where $y\{ij\}$ is a cost-effectiveness metric for project i in sector j. The model integrates multi-level project data to estimate sector-specific effects and overall cost-benefit ratios, with inference based on posterior distributions. The analysis demonstrates the model's utility for synthesising heterogeneous project data. A key finding is that the posterior probability of a positive return on investment for advanced systems exceeded 0.85 in three major infrastructure sectors. The model quantified substantial uncertainty, with the 95% credible interval for the overall cost-benefit ratio spanning from 1.4 to 3.1. The Bayesian hierarchical model provides a statistically robust and adaptable framework for assessing process-control systems, effectively handling real-world data variability and informing value-for-money analyses. Adoption of this modelling approach is recommended for future infrastructure project evaluations. Practitioners should prioritise the collection of standardised cost and performance metrics to fully leverage the model's hierarchical structure. Bayesian inference, cost-benefit analysis, infrastructure management, probabilistic modelling, project evaluation This study contributes a novel, generalisable Bayesian hierarchical modelling methodology for the economic assessment of engineering technologies, demonstrating its application to process-control systems with a specific case.

Keywords: *Bayesian hierarchical modelling, cost-effectiveness analysis, process control systems, South African infrastructure, engineering project evaluation*

Article Highlights

- Develops a novel Bayesian hierarchical model for cost-effectiveness analysis.
- Quantifies substantial uncertainty with a 95% credible interval for cost-benefit ratio from 1.4 to 3.1.
- Provides a robust framework for synthesising heterogeneous, multi-level project data.
- Demonstrates model utility for engineering decision-making in resource-constrained environments.

Methodological Contribution

Presents a generalisable Bayesian hierarchical modelling framework, formalised as $y_{ij} \sim \text{Normal}(\alpha_j + \beta X_{ij}, \sigma^2)$, $\alpha_j \sim \text{Normal}(\mu_{\alpha}, \tau^2)$, for the economic assessment of engineering technologies.

This study provides a statistically robust tool for infrastructure project evaluation.