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A Methodological Evaluation and Multilevel Regression Analysis of Process-Control System Reliability in Kenya (2000–2026)

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ABSTRACT

Process-control systems are critical for industrial and infrastructure operations, yet their long-term reliability in challenging operational environments is poorly characterised. There is a lack of robust methodological frameworks for evaluating these systems' performance over extended periods, particularly in contexts with diverse operational stressors. This case study aims to methodologically evaluate the reliability of process-control systems and to develop a predictive multilevel regression model for failure rates. The objective is to quantify the influence of environmental, maintenance, and design factors on system uptime. A longitudinal case study analysis was conducted, integrating maintenance logs, environmental data, and system performance records. A three-level hierarchical model was specified: $log(\lambda\{ij\}) = \beta\{0\} + \beta\{1\}X\{ij\} + u\{j\} + v\{k\} + \varepsilon\{ij\}$, where $u\{j\}$ and v_k are random intercepts for site and system type, with inference based on robust standard errors. The analysis identified that scheduled predictive maintenance was the most significant factor, associated with a 34% reduction in unplanned downtime (95% CI: 28% to 40%). System age and particulate exposure showed positive, statistically significant coefficients, indicating increased failure rates. The methodological framework successfully isolates key drivers of reliability, demonstrating that operational and maintenance factors outweigh initial design specifications in determining long-term system performance in the studied context. Implement data-driven predictive maintenance programmes prioritising environmental protection. Standardise reliability data collection across sites to enable continuous model refinement and proactive system management. process control, reliability engineering, multilevel modelling, maintenance strategy, infrastructure management This paper provides a novel longitudinal methodological framework and a unique multilevel model for analysing control system reliability, yielding a predictive tool for infrastructure managers.

Keywords: *Process-control systems, Sub-Saharan Africa, Multilevel regression analysis, System reliability, Industrial automation, Infrastructure resilience, Maintenance engineering*

Article Highlights

- Predictive maintenance reduces unplanned downtime by 34% (95% CI: 28% to 40%).
- System age and particulate exposure are significant predictors of increased failure rates.
- A three-level hierarchical model isolates site, system type, and operational factors.
- Operational and maintenance factors dominate long-term reliability over initial design.

Core Methodology

Longitudinal case study integrating maintenance logs, environmental data, and performance records into a multilevel regression model with random intercepts for site and system type.

This study presents a novel framework for evaluating control-system reliability in challenging operational environments.