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Modelling Plant Performance and Availability Through Maintenance and Workforce Dynamics: A System Dynamics Approach

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Abstract

This paper presents a system dynamics framework for modelling thermal power plant performance and availability through the integrated lens of maintenance strategy and workforce dynamics. The research addresses the challenge of quantifying complex causal relationships between operational decisions, personnel competencies, and long-term asset performance relationships whose non-linear and delayed character renders conventional analytical methods inadequate. A simulation environment was developed incorporating four interacting modules: Equilibrium Plant Condition, Performance Metrics, Personnel Dynamics, and Maintenance Strategy Integration. The model captures dynamic interactions among Design Base Maintenance (DBM), Operating Basis Maintenance (OBM), and Plant Improvement Maintenance (PIM) strategies while accounting for workforce skill acquisition, attrition, and proficiency decay. Validation draws on ten years of historical operational data from multiple South African coal-fired generating stations. Quantitative accuracy metrics include Mean Absolute Percentage Error (MAPE = 4.2%), Root Mean Square Error (RMSE = 2.8%), and Theil's Inequality Statistics ($U^m = 0.15$, $U^s = 0.23$, $U^c = 0.62$). Key findings establish that Energy Availability Factor (EAF) recovery correlates strongly with personnel proficiency ($r = 0.82$, $p < 0.001$) and that workforce dynamics generate characteristic 18–24-month oscillatory cycles in plant performance metrics. DBM effectiveness declines by approximately 15% when personnel proficiency falls below a critical 70% threshold, and OBM utilisation exceeding 40% correlates with self-reinforcing increases in the Unplanned Capability Loss Factor ($r = 0.73$, $p < 0.001$). Sensitivity analysis identifies personnel proficiency ($S = 1.42$), training duration ($S = 0.89$), and maintenance budget ($S = 0.67$) as the most influential parameters. A 10% increase in annual staff turnover is associated with a 2.3% EAF decline (95% CI: −3.1% to −1.5%), representing an annual revenue impact of approximately USD 3.07 million per 600 MW unit. The validated model provides a practical decision-support tool for maintenance investment prioritisation and workforce planning in thermal power generation.

Keywords
System Dynamics, Maintenance Optimization, Energy Availability Factor, Workforce Dynamics, Thermal Power Plants