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Reliability-Centered Maintenance and FMEA for Booster Pump Systems in Utility Buildings: A Case Study of Wisma PMI

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Abstract: Booster pump systems play a critical role in ensuring reliable water distribution in high-rise buildings, and inadequate maintenance practices can lead to operational disruptions and occupant complaints. This study aims to evaluate and optimize the maintenance strategy of the booster pump system at the PMI Guesthouse Building, South Jakarta, in response to recurrent failures and excessive noise that negatively affected service quality and building occupancy. A reliability-oriented engineering approach was adopted by integrating Reliability Centered Maintenance (RCM) and Failure Mode and Effects Analysis (FMEA). The study employed a case-based design using field observations, operational and downtime records from 2023, and interviews with maintenance personnel. Failure modes were systematically identified and evaluated using severity, occurrence, and detection criteria, followed by RCM-based task selection and performance validation through noise measurements before and after corrective action. The results indicate that a limited number of high-risk components, particularly the mounting system, were the primary contributors to vibration and acoustic disturbances. Implementation of targeted reliability-based maintenance actions resulted in an estimated reduction in failure severity of up to 20% and a decrease in noise levels of approximately 20 dB. These findings demonstrate the effectiveness of integrating FMEA-based risk prioritization within an RCM framework for improving system reliability and operational comfort. The study provides practical implications for facility managers by offering a structured and replicable maintenance model that links analytical risk assessment to measurable performance improvements. The originality of this research lies in the application of an integrated RCM–FMEA framework to a building utility system using actual field data and comfort-related indicators, extending existing maintenance studies that predominantly focus on industrial or design-based contexts.

Keywords: RCM; Failure Mode and Effects Analysis; Booster Pump; Building Utility System; Noise Reduction FMEA, Maintenance Engineering, Building Systems

INTRODUCTION

High-rise building water distribution systems rely heavily on booster pumps as critical utility assets, since reliability disruptions and inadequately structured maintenance practices can trigger operational disturbances and even unplanned shutdowns in interconnected systems, particularly in aging facilities (Arsalan et al., 2019; Shao et al., 2020; Zhou et al., 2021). Field evidence from Wisma PMI indicates recurring booster pump failures that directly compromise clean water availability reflected by complaints regarding non-functional toilets and washbasins as well as excessive noise and vibration during fault conditions. Operational records from 2023–2024 demonstrate fluctuating downtime, including September 2023 (10 hours), October 2023 (15 hours), February 2024 (10 hours), March 2024 (10 hours), May 2024 (7 hours), July 2024 (7 hours), and August 2024 (5 hours), revealing uncontrolled failure patterns that necessitate a reliability-based maintenance approach to mitigate operational disruptions and enhance occupant comfort.

Recent studies confirm that Reliability Centered Maintenance (RCM) remains a dominant reliability-based maintenance strategy for improving system availability while optimizing maintenance costs, particularly for dynamic equipment (Cavalcante & Lopes, 2019; Li & Yang, 2004). Contemporary research demonstrates that RCM, when grounded in functional analysis and component criticality, enables more effective maintenance planning and resource allocation, especially when supported by real operational failure data (Patil et al., 2022; H. Wang et al., 2007). Nevertheless, recent literature also highlights that classical RCM frameworks tend to be resource-intensive and require contextual adaptation to remain practical for non-manufacturing systems such as building utilities.

Complementing RCM, Failure Mode and Effects Analysis (FMEA) has been widely applied in the last five years as a structured risk assessment tool for pump systems (Carpitella & Certa, 2018; Kumru & Kumru, 2019). Recent studies emphasize the effectiveness of FMEA in identifying failure modes, evaluating their impacts on system performance, and prioritizing mitigation actions through Risk Priority Number (RPN) analysis (Karek et al., 2025; Sharma, 2021). Methodological advancements further enhance FMEA by integrating fuzzy logic and machine learning techniques, reducing subjectivity and improving the accuracy of failure risk evaluation (Sun et al., 2025; W. H. Wang et al., 2023). Despite these advances, most FMEA-based studies remain focused on failure ranking rather than linking risk assessment outcomes to actionable, reliability-based maintenance decision frameworks such as RCM, particularly using condition-based operational indicators.

Recent studies on booster pump systems in utility and high-rise buildings predominantly address design, operational optimization, and energy efficiency (He & Wang, 2022; Zhang & Liu, 2020). Studies report that variable-speed control strategies, coordinated pump operation, and real-time monitoring systems can significantly reduce energy consumption and extend equipment service life (Bae et al., 2025). However, field-oriented issues such as recurring downtime, mechanical degradation, excessive vibration, and noise continue to pose operational challenges in building utility systems, especially in facilities with high dependency on continuous water supply (Sun et al., 2025). Overall, although RCM, FMEA, and booster pump systems have been extensively investigated as separate domains, integrated studies that combine RCM and FMEA for booster pump systems in utility buildings supported by actual downtime data and operational comfort indicators remain limited, indicating a clear research gap that warrants further investigation.

This study aims to address the identified gap in the literature by developing and applying an integrated RCM–FMEA framework for booster pump systems in utility buildings, grounded in actual field performance data. The research specifically seeks to identify critical components and dominant failure modes of the booster pump system, prioritize maintenance actions based on quantified risk levels, and evaluate the impact of reliability-based interventions on operational indicators such as downtime, vibration, and noise. Through a real-case application at Wisma PMI, this study intends to provide a practical and replicable maintenance model that enhances system reliability and operational comfort in building utility systems.

This study hypothesizes that the integration of FMEA-based risk prioritization into an RCM-driven maintenance strategy will significantly improve the operational reliability of booster pump systems in utility buildings. It is assumed that recurring disturbances manifested as unplanned downtime, excessive vibration, and noise are primarily caused by failures in a limited number of high-risk components, and that targeted maintenance actions on these components will reduce failure frequency and severity. Consequently, the application of an integrated RCM–FMEA approach is expected to yield measurable improvements in system stability and maintenance effectiveness compared to conventional reactive maintenance practices.

RESEARCH METHOD

Unit of Analysis and Research Design

The unit of analysis in this study is the booster pump system within the water distribution infrastructure of the Wisma PMI building in Jakarta. The analysis covers key mechanical and functional components, including the pump body, impeller, shaft, rotor–

stator assembly, mechanical seal, and mounting system, as well as their failure behavior and maintenance performance under actual operating conditions. A quantitative, reliability-oriented engineering case study design was adopted. The integration of Reliability Centered Maintenance (RCM) and Failure Mode and Effects Analysis (FMEA) was selected to provide a structured, data-driven framework for identifying critical components, prioritizing failure risks, and determining effective maintenance policies. This design is appropriate for complex building utility systems where maintenance decisions must be aligned with functional criticality and observed failure consequences.

Data Sources and Collection

The study employed primary and secondary data sources. Primary data were obtained through direct field observations of the booster pump installation, including system configuration, component conditions, and routine maintenance activities, as well as semi-structured interviews with operational and maintenance personnel to capture insights on recurring failures and maintenance decision-making. Secondary data consisted of operational logs, downtime records, and monthly maintenance reports for the period 2023–2024, providing quantitative evidence of system performance and failure history. Data collection also included noise level measurements and operational condition observations conducted before and after the implementation of corrective maintenance actions to assess changes related to vibration and acoustic behavior.

Data Analysis Procedure

Data analysis was conducted in sequential stages. First, descriptive statistical analysis was applied to establish baseline performance indicators, including operating hours, failure frequency, and downtime duration. Second, FMEA was performed by assigning severity, occurrence, and detection ratings to each component to calculate the Risk Priority Number (RPN) and identify critical failure modes. Third, the RCM logic framework was applied to translate FMEA results into maintenance policies based on functional importance and failure consequences, including condition-based inspections and targeted preventive actions. Finally, a comparative before–after analysis was conducted to evaluate the effectiveness of corrective actions in improving reliability and reducing vibration and noise. This integrated analytical approach ensured that findings were empirically grounded and operationally actionable.

RESULT AND DISCUSSION

Failure Risk Identification of Booster Pump Components

Failure Mode and Effects Analysis (FMEA) was conducted to identify critical components contributing to reliability degradation in the booster pump system at Wisma PMI. The analysis focused on three major component groups pump unit, rotor–stator assembly, and mounting system by evaluating severity, occurrence, and detection to obtain the Risk Priority Number (RPN), as presented in Table 2.

Table 2. FMEA Identification

Part	Function	Potential Failure Mode	Potential Effect of Failure	S	Potential Causes of Failure	O	Current Control	D	RPN	Total
Pump										**69**
1.1	Provides pressure to the pipeline	Impeller stuck	Material not resistant to corrosion	3	Rusting	2	Periodic maintenance	3	18	
1.1	Provides pressure to the pipeline	Loose bolts	Material erosion	3	Insufficient tightening	3	Periodic maintenance	2	27	
1.1	Provides pressure to the pipeline	Pump leaking	Pump unable to prime	4	Air leakage	2	Periodic maintenance	2	16	
Rotor & Stator										**96**
1.4	Drives shaft/impeller	Bearing stuck	Damage due to insufficient lubrication	4	Rusting	4	Periodic maintenance	3	48	
1.4	Drives shaft/impeller	Coil burnt	Incomplete rotation	4	Unstable electrical voltage	3	Voltage measurement & inspection	4	48	
Mounting										**100**
1.8	Holds vibration and sound absorber	Unable to withstand vibration and noise	Rubber cracking or hardening	5	Inappropriate material	5	Periodic maintenance & material testing	4	100	

The results in Table 2 indicate that the mounting system exhibits the highest total RPN, significantly exceeding those of the pump and rotor–stator assemblies. This high-risk level is primarily attributed to rubber hardening and cracking, which reduce the mounting's ability to absorb vibration and noise. The rotor–stator assembly ranks second, with critical failure modes related to bearing seizure due to inadequate lubrication and coil burning caused by unstable voltage. In contrast, failures within the pump body such as impeller corrosion, leakage, and loose bolts present moderate risk levels.

These findings reveal that components responsible for vibration isolation and mechanical support play a dominant role in operational disturbances, suggesting that reliability issues are not solely driven by hydraulic performance but also by structural and dynamic factors.

Functional Hierarchy and Reliability Classification Using RCM

The booster pump system was decomposed into a functional hierarchy as part of the RCM implementation to support reliability-centered decision-making. Table 3 presents the structural breakdown of subsystems and components, while Table 4 summarizes the corresponding functional failures.

Table 3. Hierarchy of Functions in the Booster Pump System

Machine Item	Subsystem ID	Component	Machine Component Description
Booster Pump Machine	1.1	Drive Motor	Main motor that drives the pump mechanism
	1.2	Rubber Pulley Coupling	Flexible coupling that connects the motor and impeller
	1.3	Casing	Housing that protects internal pump components
	1.4	Impeller	Rotating element that generates water flow
	1.5	Shaft	Mechanical shaft transmitting rotation to the impeller
	1.6	Coupling	Connector transferring motion between mechanical parts
	1.7	Mechanical Seal	Seal that prevents fluid leakage along the shaft
	1.8	Spring Mounting	Vibration-absorbing mounting component
	1.9	Pressure Gauge	Instrument measuring system pressure
	1.1	Pressure Switch	Automatic switch controlling pump operation based on pressure
	1.11	Pressure Tank	Tank maintaining system pressure stability

Table 4. Functional Analysis of System Failures

Subsystem ID	System Component	System Function	System Failure
1.1	Motor and Stator	Drives the impeller	Coil burning
1.2	Pulley Rubber Coupling	Provides connection between stator and impeller	Rubber wear and abrasion
1.3	Casing	Protects against air leakage	Cracking
1.4	Impeller	Rotates to draw water	Corrosion and thinning
1.5	Shaft	Rotates the impeller	Abrasion, cracking, and fracture
1.6	Coupling / Packing Seal	Prevents leakage	Drying and brittleness
1.7	Mechanical Seal	Prevents leakage and stabilizes the shaft	Breakage and abrasion

The functional hierarchy clarifies how individual component failures propagate system-level consequences. Failures such as coil burning, seal degradation, impeller corrosion, and shaft fracture directly impair water supply continuity and system stability. This mapping confirms that many failures identified in the FMEA stage originate from components with critical functional roles, particularly those related to energy transmission, sealing, and vibration control.

By linking functional importance with observed failure mechanisms, the RCM framework provides a structured basis for prioritizing maintenance actions beyond routine periodic maintenance.

Maintenance Task Selection and Performance Improvement

Logic Tree Analysis was applied to classify booster pump failure modes based on empirical evidence of failure occurrence, safety implications, and operational outage, as summarized in Table 5.

Table 5. Logic Tree Analysis

No	Component	Function	Failure Mode	Evidence (Y/N)	Safety (Y/N)	Outage (Y/N)	Category
1	Motor and Stator	Drives the impeller	Coil burning	Y	Y	Y	B
2	Pulley Rubber Coupling	Connects stator to impeller	Rubber wear and abrasion	N	Y	Y	C
3	Casing	Protects against air leakage	Cracking	Y	N	Y	C

No	Component	Function	Failure Mode	Evidence (Y/N)	Safety (Y/N)	Outage (Y/N)	Category
4	Impeller	Rotates to draw water	Corrosion / thinning	N	N	Y	B
5	Shaft	Rotates the impeller	Abrasion, cracking, fracture	Y	Y	Y	B
6	Coupling / Packing Seal	Prevents leakage	Drying and brittleness	Y	N	Y	C
7	Mechanical Seal	Prevents leakage & stabilizes shaft	Breakage and abrasion	N	N	Y	C
8	Coupling Seal	Prevents leakage	Drying and brittleness	Y	N	Y	C
9	Mounting	Absorbs vibration and sound	Rubber hardening or breakage	Y	Y	Y	B

The results indicate that several components namely the motor–stator assembly, shaft, impeller, and mounting system were classified as Category B, indicating high criticality due to their combined impact on safety, service continuity, and system reliability. Among these components, the mounting system exhibited a distinct failure profile, as its degradation primarily affected vibration transmission and acoustic disturbance rather than hydraulic or electrical performance. This characteristic identified the mounting system as the most plausible source of the recurrent noise complaints observed during pump operation. Accordingly, a Finding Failure (FF) maintenance task was selected to verify the operational condition of the mounting system through targeted noise and vibration assessment. Noise measurements conducted prior to corrective action, as presented in Table 6, reveal elevated sound pressure levels across all measurement distances, with the highest values recorded at 3 m and 5 m from the pump unit.

Table 6. Baseline Noise Levels of the Booster Pump System

Radius Machine	Noise Level	Measurement Data
10 meters	**72 db**	

Radius Machine	Noise Level	Measurement Data
5 meters	**83 db**	
3 meters	**84db**	

These measurements indicate ineffective vibration isolation, suggesting that mechanical excitation from rotating components was being directly transmitted to the surrounding structure. Following the replacement of the rubber mounting with a spring-based mounting system, noise levels were remeasured, as shown in Table 7.

Table 7. Noise Level Measurements After Corrective Action

Radius Machine	Noise Level	Measurement Data
10 meters	**60db**	
5 meters	**46db**	
3 meters	**72db**	

The post-repair data demonstrate a substantial reduction in noise intensity**,** particularly at medium and close-range distances. The observed reduction confirms that the mounting system played a dominant role in vibration propagation and acoustic emission within the booster pump installation.

The measurable improvement in noise performance after the corrective action provides empirical validation of the selected FF task and supports the effectiveness of risk-based maintenance prioritization derived from the integrated Logic Tree and FMEA results.

Discussion

The results demonstrate that reliability issues in the booster pump system at Wisma PMI are primarily driven by failures in a limited number of high-risk components rather than uniform degradation across the system. The FMEA findings consistently identify the mounting system as the most critical contributor to vibration and noise disturbances, while the RCM functional analysis explains how such failures propagate operational impacts throughout the system.

These findings align with recent studies emphasizing risk-based maintenance strategies for dynamic equipment yet extend prior research by explicitly linking FMEA risk prioritization with RCM task selection and measurable performance outcomes. Unlike studies that focus solely on failure ranking, this research demonstrates how integrated RCM–FMEA analysis can directly inform actionable maintenance decisions.

From an interpretive perspective, the significant reduction in noise levels following the mounting replacement highlights that maintenance effectiveness should be evaluated not only through downtime reduction but also through operational comfort indicators. This perspective broadens conventional reliability assessment by incorporating user-oriented performance metrics.

In practical terms, the study shows that targeted, reliability-driven maintenance interventions can substantially improve system stability without extensive redesign or capital investment. However, the findings are limited to a single case study, and future research should examine long-term reliability trends and apply the framework to other building utility systems.

Overall, this study contributes a structured and replicable maintenance model that integrates FMEA-based risk assessment with RCM task planning, offering a practical approach for improving reliability and operational comfort in multi-storey building infrastructure.

CONCLUSION

The application of a structured reliability-based maintenance framework proves critical for improving the operational performance and service continuity of booster pump systems in high-rise buildings. The integrated use of Reliability Centered Maintenance (RCM) and Failure Mode and Effects Analysis (FMEA) enable systematic identification of critical components and dominant failure modes, with results indicating that the mounting system plays a decisive role in vibration transmission and excessive noise generation. Field-based evidence shows that operational disturbances in the studied system are closely associated with mechanical degradation, inadequate vibration isolation, and limitations in conventional preventive inspection practices.

The main scientific contribution of this research lies in the operationalization of an integrated RCM–FMEA approach for building utility systems using actual operational and downtime data rather than purely design-based or theoretical assumptions. The study extends existing maintenance literature by explicitly linking risk-based component prioritization to measurable performance indicators, including downtime, vibration, and noise levels. Empirical validation of a targeted corrective action namely, the replacement of a rubber mounting with a spring-based system demonstrates how reliability-centered analytical results can be translated into effective and practical maintenance interventions. The proposed framework provides a replicable reference for enhancing maintenance effectiveness in similar utility infrastructure contexts.

Several limitations should be acknowledged in interpreting the findings. The investigation was conducted as a single-case study within one building facility, which may constrain the generalizability of the results to other system configurations or operational environments. In addition, performance evaluation emphasized short-term acoustic and vibration improvements without extended observation of long-term reliability trends or lifecycle cost impacts. Future studies are therefore encouraged to apply the proposed framework across multiple facilities, integrate long-term condition monitoring data, and incorporate economic performance metrics to strengthen the robustness and broader applicability of reliability-based maintenance strategies for building utility systems.

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