Reliability-Centered Maintenance Assessment of Centrifugal Pumps in Omani Oil and Gas Processing Plants

Khulood Mohammed Abdullah Al-Rajhi[1], Dadapeer Doddamani[2]

[1]*Research Scholar, Department of Engineering, College of Engineering and Technology, University of Technology and Applied Sciences, Muscat, Sultanate of Oman.*

[2]*Lecturer, Department of Engineering, College of Engineering and Technology, University of Technology and Applied Sciences, Muscat, Sultanate of Oman.*

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Abstract - *Centrifugal pumps are among the most critical rotating equipment in oil and gas processing plants, where their operational reliability directly influences production continuity, equipment availability, maintenance costs, and process safety. In Omani oil and gas facilities, pump failures resulting from component degradation, improper maintenance planning, and reactive maintenance practices contribute to unplanned shutdowns and increased operational expenditure. Although reliability assessment techniques and maintenance optimization methods have been extensively investigated, the practical integration of reliability engineering principles into a structured Reliability-Centered Maintenance (RCM) assessment framework for centrifugal pumps remains limited. This study presents a systematic RCM assessment methodology aimed at improving maintenance planning and asset management for centrifugal pumps operating in Omani oil and gas processing plants. The proposed methodology integrates historical maintenance data assessment, functional analysis, failure mode identification, asset criticality assessment, maintenance decision logic, and maintenance task selection into a comprehensive framework for maintenance planning. The study emphasizes a structured engineering approach for evaluating equipment functions, identifying critical failure consequences, prioritizing maintenance activities, and selecting appropriate preventive and condition-based maintenance tasks. Rather than focusing on detailed quantitative reliability metrics, the framework establishes a practical decision-support methodology that enables maintenance engineers to transition from reactive maintenance to proactive and reliability-centered maintenance practices. The proposed RCM assessment framework provides a systematic basis for improving maintenance effectiveness, optimizing inspection strategies, enhancing equipment availability, reducing unplanned downtime, and supporting informed maintenance decision-making. Furthermore, the framework offers a scalable approach that can be adapted to similar rotating equipment across the oil and gas sector. The outcomes of this work contribute to the implementation of structured asset management practices and provide a foundation for future integration with digital condition monitoring, predictive maintenance, and Industrial Internet of Things (IIoT)-based maintenance systems. The detailed quantitative reliability analysis and maintenance optimization results are reserved for subsequent studies, while the present work establishes the methodological foundation for reliability-centered maintenance implementation in Omani oil and gas processing facilities.*

Key Words: Reliability-Centered Maintenance, Centrifugal Pumps, Maintenance Assessment, Preventive Maintenance, Condition-Based Maintenance, Maintenance Decision Framework.

1. INTRODUCTION

Centrifugal pumps are among the most extensively used rotating equipment in the oil and gas industry, serving a vital role in transporting crude oil, refined petroleum products, produced water, chemicals, and other process fluids throughout upstream, midstream, and downstream facilities. Their ability to deliver continuous flow under varying operating conditions makes them indispensable for maintaining uninterrupted production processes. Because these pumps operate continuously in demanding environments characterized by fluctuating pressures, temperatures, and fluid properties, their operational reliability is essential for ensuring plant productivity, process safety, and overall operational efficiency.

The oil and gas sector is highly dependent on equipment reliability to achieve production targets while minimizing operational risks. Any unexpected failure of centrifugal pumps can result in production interruptions, equipment damage, environmental incidents, increased maintenance costs, and significant economic losses. Consequently, maintenance management has become a critical component of asset management strategies adopted by modern oil and gas industries. Effective maintenance practices not only improve equipment availability but also enhance operational safety, optimize resource utilization, and extend equipment service life.

Historically, maintenance activities in many industrial facilities have relied on corrective or time-based preventive maintenance approaches. Corrective maintenance is performed only after equipment failure occurs, often resulting in unplanned shutdowns and costly emergency repairs. Time-based preventive maintenance, although more systematic, may still lead to unnecessary component replacement or fail to detect developing failures occurring between scheduled inspections. These conventional maintenance approaches frequently increase maintenance expenditure while failing to maximize equipment reliability. The increasing complexity of industrial processing plants has encouraged organizations to adopt reliability-based maintenance methodologies that focus on understanding equipment behavior, identifying critical failure mechanisms, and selecting maintenance actions according to equipment condition and operational criticality. Reliability engineering provides analytical techniques for evaluating equipment performance and identifying factors that influence operational failures. These techniques support maintenance planning by enabling maintenance engineers to prioritize critical equipment and allocate maintenance resources more effectively.

Among the various maintenance methodologies, Reliability-Centered Maintenance (RCM) has emerged as one of the most effective approaches for optimizing maintenance programs in safety-critical and asset-intensive industries. Originally developed for the aviation industry, RCM has since been widely adopted in power generation, petrochemical processing, manufacturing, transportation, and oil and gas operations. The primary objective of RCM is to preserve the intended functions of equipment by identifying functional failures, understanding failure consequences, and selecting technically appropriate and economically feasible maintenance tasks.

Unlike conventional maintenance strategies, RCM emphasizes maintaining system functionality rather than merely preventing component failure. The methodology systematically evaluates equipment functions, potential failure modes, failure effects, operational consequences, and maintenance alternatives before selecting the most appropriate maintenance policy. This structured decision-making process enables organizations to balance maintenance costs with equipment reliability, thereby improving plant availability and operational efficiency.

In the context of centrifugal pumps, numerous failure mechanisms contribute to equipment degradation, including bearing wear, mechanical seal deterioration, shaft misalignment, impeller damage, cavitation, lubrication deficiencies, excessive vibration, and improper operating conditions. These failures may develop gradually over time or occur suddenly due to unexpected operational disturbances. Since many of these degradation mechanisms are detectable during early stages, structured maintenance assessment provides opportunities to implement preventive or condition-based interventions before catastrophic failures occur.

The Sultanate of Oman possesses a mature oil and gas industry that forms a significant pillar of the national economy. Oil production facilities operate continuously under demanding environmental conditions, where high ambient temperatures, dust, varying fluid compositions, and continuous operation place considerable stress on rotating equipment. Maintaining high equipment reliability is therefore essential for ensuring production continuity, minimizing downtime, and achieving operational excellence. Consequently, oil and gas operators increasingly seek maintenance strategies capable of improving asset reliability while simultaneously controlling maintenance costs and optimizing maintenance resources.

Although reliability analysis methods such as Failure Mode and Effects Analysis (FMEA), Weibull analysis, fault tree analysis, and condition monitoring techniques have been extensively reported in the literature, many published studies examine these techniques independently. Similarly, recent advances in digital maintenance technologies including Industrial Internet of Things (IIoT), smart sensors, and predictive analytics have enhanced condition monitoring capabilities, yet their integration into practical maintenance decision-making remains limited. There remains a need for a comprehensive engineering framework that systematically combines reliability assessment with maintenance planning in a manner that can be readily implemented by maintenance engineers within industrial environments.

2. PROBLEM STATEMENT

Despite considerable investment in maintenance programs, centrifugal pumps in oil and gas processing facilities continue to experience failures that lead to equipment downtime, production interruptions, increased maintenance costs, and reduced operational efficiency. Many organizations still rely heavily on reactive maintenance practices or fixed-interval preventive maintenance schedules that do not adequately consider equipment criticality, failure consequences, or degradation behavior. Such maintenance approaches often result in inefficient allocation of maintenance resources and unnecessary replacement of components while failing to prevent unexpected failures.

Existing reliability studies frequently emphasize quantitative reliability indices without providing a structured methodology for translating reliability information into practical maintenance decisions. Conversely, maintenance studies often focus on maintenance scheduling without integrating reliability engineering concepts into the decision-making process. This disconnect creates challenges for maintenance engineers attempting to develop maintenance programs that simultaneously improve equipment reliability, optimize maintenance resources, and reduce operational risks.

Therefore, there is a need for a systematic Reliability-Centered Maintenance assessment framework that integrates reliability engineering principles with maintenance decision logic to support effective maintenance planning for centrifugal pumps operating in Omani oil and gas processing plants.

3. RESEARCH OBJECTIVES

- To review the operational significance and common failure mechanisms of centrifugal pumps in oil and gas processing facilities.
- To establish a systematic Reliability-Centered Maintenance assessment methodology based on reliability engineering principles.
- To propose an integrated maintenance assessment framework that can be adopted for maintenance planning and continuous improvement in industrial oil and gas facilities.

4. RESEARCH METHODOLOGY

The proposed methodology adopts a structured Reliability-Centered Maintenance (RCM) approach to assess and improve the maintenance management of centrifugal pumps in Omani oil and gas processing plants. The process begins with the collection of historical maintenance records and equipment specifications, followed by functional analysis to identify the intended operating functions of the pumps. Potential failure modes and their causes are then identified and evaluated based on their operational, safety, environmental, and economic consequences. Subsequently, an asset criticality assessment is conducted to prioritize equipment according to its impact on plant operation. Based on the criticality assessment, maintenance decision logic is applied to determine the most appropriate maintenance strategy, including preventive, condition-based, predictive, or corrective maintenance. Appropriate maintenance tasks are then selected and incorporated into a maintenance planning framework, which is continuously reviewed and improved using maintenance feedback and performance monitoring to enhance equipment reliability, availability, and maintenance effectiveness.

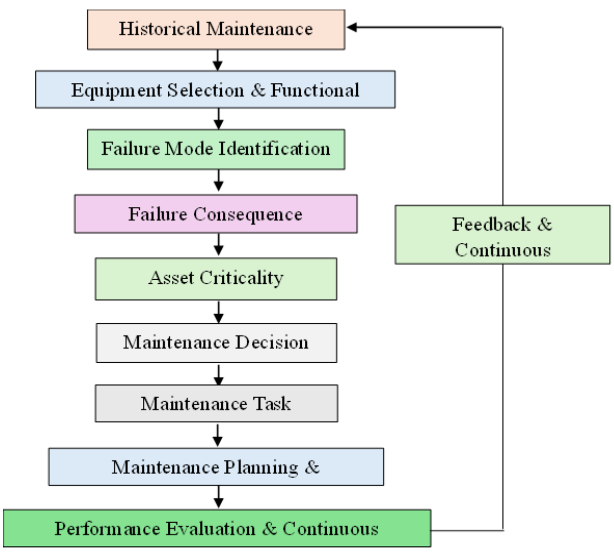

Fig-1 Research Methodology

5. PROPOSED RELIABILITY-CENTERED MAINTENANCE ASSESSMENT FRAMEWORK

Reliability-Centered Maintenance (RCM) is a systematic maintenance methodology that identifies the most effective maintenance strategies by evaluating equipment functions, failure modes, operational consequences, and asset criticality. In oil and gas processing plants, centrifugal pumps are critical assets whose failures can lead to production losses, increased maintenance costs, safety risks, and environmental impacts. To address these challenges, this study proposes an integrated RCM assessment framework that combines functional analysis, failure mode identification, consequence assessment, asset criticality evaluation, maintenance decision logic, and maintenance task selection into a structured methodology for centrifugal pumps in Omani oil and gas facilities. The framework provides a practical approach for prioritizing maintenance activities, improving maintenance planning, and supporting the transition from reactive to proactive maintenance practices, while establishing a foundation for future integration with predictive maintenance and Industrial Internet of Things (IIoT) technologies.

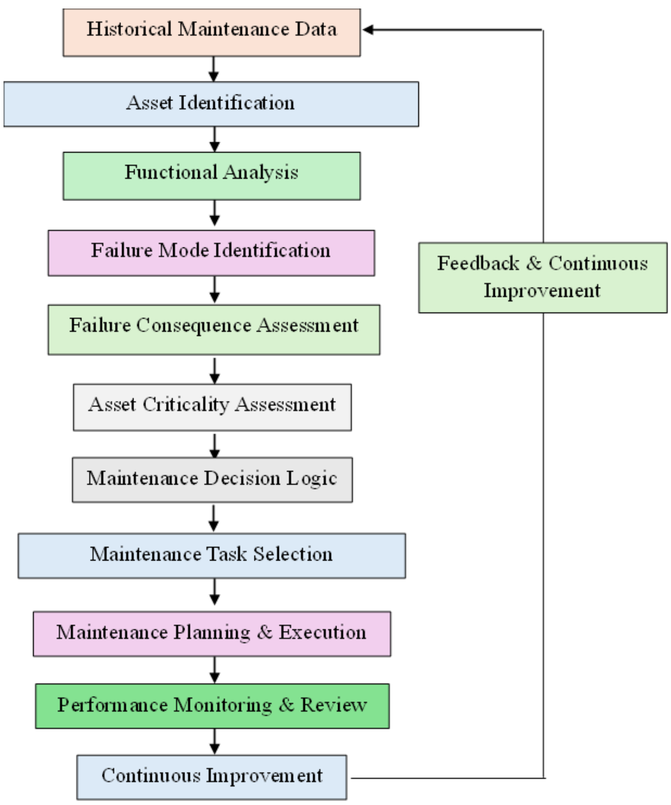

Fig-2: Proposed Reliability-Centered Maintenance Assessment Framework

The proposed Reliability-Centered Maintenance (RCM) assessment framework provides a systematic methodology for improving the reliability and maintenance management of centrifugal pumps in Omani oil and gas processing plants.

The framework begins with the collection of historical maintenance records and equipment specifications to establish a comprehensive asset database and understand the operational role of each pump. Functional analysis is then conducted to define the intended operating requirements and identify potential functional failures. Based on maintenance history and engineering knowledge, failure modes and their operational, safety, environmental, and economic consequences are evaluated, followed by an asset criticality assessment to prioritize equipment according to its impact on production and operational risk. The framework subsequently applies maintenance decision logic to determine the most suitable maintenance strategy, including preventive, condition-based, predictive, scheduled replacement, or corrective maintenance. Appropriate maintenance tasks are selected and incorporated into maintenance planning and implementation. Finally, equipment performance is continuously monitored using maintenance feedback and key performance indicators to refine maintenance strategies, enhance equipment reliability, optimize maintenance resources, and support continuous improvement and future integration with Industry 4.0 and IIoT-enabled asset management systems.

Table -1: Summary of the Proposed RCM Framework

Stage	Purpose	Main Activities	Output
Asset Identification	Identify critical pumps	Equipment inventory, specifications	Asset database
Functional Analysis	Define intended functions	Process requirements, operating conditions	Functional requirements
Failure Mode Identification	Identify possible failures	Historical records, maintenance reports	Failure modes
Consequence Assessment	Evaluate impact	Safety, production, environment	Failure consequences
Asset Criticality	Prioritize assets	Risk ranking	Criticality level
Decision Logic	Select maintenance policy	Preventive, CBM, PdM, Corrective	Maintenance strategy
Task Selection	Choose maintenance tasks	Inspection, monitoring, replacement	Maintenance schedule
Continuous Improvement	Improve maintenance	KPI review, feedback	Updated maintenance plan

Table -2: Typical Failure Modes of Centrifugal Pumps

Category	Typical Failure Modes
Mechanical	Bearing wear, seal wear, shaft misalignment, coupling damage
Hydraulic	Cavitation, impeller erosion, recirculation, flow instability
Electrical	Motor winding failure, insulation degradation, current imbalance
Lubrication	Oil contamination, grease degradation, lubricant leakage
Operational	Dry running, blocked suction, valve malfunction, process upset

Table -3: Failure Consequences

Consequence	Examples
Safety	Injury, fire, explosion
Environmental	Oil leakage, contamination
Operational	Shutdown, production loss
Maintenance	Repair frequency, spare consumption
Economic	Maintenance cost, energy loss

Table -4: Asset Criticality Criteria

Criterion	Rating
Safety	High / Medium / Low
Environment	**High / Medium / Low**
Production	High / Medium / Low
Availability	**High / Medium / Low**
Repair Complexity	High / Medium / Low
Spare Availability	**High / Medium / Low**

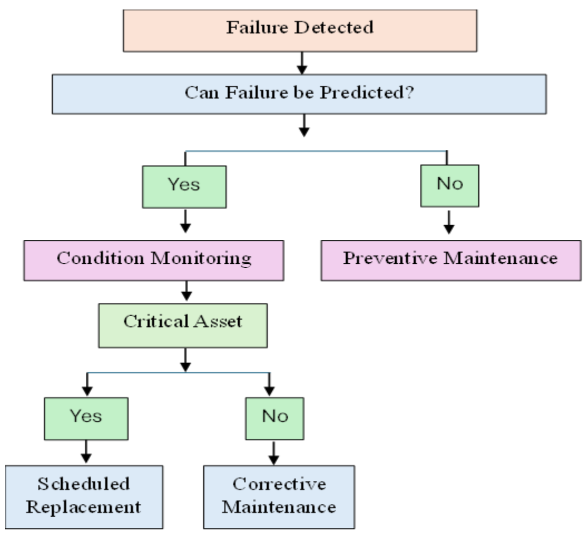

Fig-3: Decision Logic with One Flowchart

The maintenance decision logic provides a structured process for selecting the most appropriate maintenance strategy based on failure predictability and asset criticality. This approach enables maintenance engineers to implement preventive, condition-based, predictive, scheduled replacement, or corrective maintenance, thereby improving equipment reliability while optimizing maintenance resources and reducing unplanned downtime.

Table -5: Maintenance Tasks

Failure Mode	Inspection	Monitoring	Maintenance Action
Seal Leakage	Visual	Leak Detection	Replace Seal
Bearing Wear	Lubrication	Vibration	Bearing Replacement
Misalignment	Laser Alignment	Vibration	Shaft Alignment
Cavitation	Hydraulic Inspection	Pressure	Correct Operating Conditions
Motor Overheating	Thermal Inspection	Temperature	Motor Servicing
Lubrication Failure	Oil Analysis	Oil Quality	Lubrication Renewal

Maintenance performance is continuously evaluated using key performance indicators such as equipment availability, downtime, maintenance compliance, repeat failures, and inspection effectiveness. Feedback obtained from maintenance activities is used to refine inspection intervals, update maintenance procedures, improve resource allocation, and enhance overall maintenance effectiveness.

6. DISCUSSION

The present study proposes a structured Reliability-Centered Maintenance (RCM) assessment framework for centrifugal pumps operating in Omani oil and gas processing plants. Unlike many studies that primarily emphasize quantitative reliability indices or condition-monitoring technologies, the proposed framework focuses on the systematic integration of reliability engineering principles into maintenance planning and decision-making. By combining equipment functional analysis, failure mode identification, asset criticality assessment, maintenance decision logic, and maintenance task selection, the framework provides a practical methodology for improving maintenance effectiveness while supporting long-term asset reliability.

The framework is intended to bridge the gap between reliability analysis and maintenance implementation. Rather than relying solely on corrective maintenance or predetermined maintenance intervals, the proposed approach enables maintenance engineers to prioritize maintenance activities based on equipment function, operational importance, and failure consequences. This transition from time-based maintenance to reliability-centered maintenance is expected to improve maintenance efficiency and enhance equipment performance throughout the asset life cycle.

7. SIGNIFICANCE OF THE PROPOSED RCM FRAMEWORK

One of the principal contributions of this study is the development of an integrated maintenance assessment framework specifically designed for centrifugal pumps in oil and gas processing plants. Although previous studies have successfully applied individual reliability tools such as Failure Mode and Effects Analysis (FMEA), Weibull analysis, and condition monitoring, these methods are often implemented independently. Consequently, maintenance personnel may obtain valuable reliability information without having a structured process for converting that information into maintenance actions.

The proposed framework addresses this limitation by establishing a logical sequence that begins with equipment functional analysis and concludes with maintenance task selection and continuous improvement. This structured methodology assists maintenance engineers in identifying critical equipment, evaluating potential failure consequences, and selecting maintenance strategies that are technically appropriate and operationally practical.

Furthermore, the framework promotes consistency in maintenance planning by providing standardized procedures for maintenance assessment. Such standardization is particularly important in large industrial facilities where maintenance decisions involve multiple departments and personnel with varying levels of technical experience.

8. PRACTICAL IMPLICATIONS FOR OMANI OIL AND GAS FACILITIES

Oil and gas processing plants in the Sultanate of Oman operate under demanding environmental and operational conditions. High ambient temperatures, continuous production schedules, corrosive process fluids, and variable operating conditions place considerable stress on rotating equipment, particularly centrifugal pumps. Under such conditions, maintaining high equipment reliability is essential for ensuring uninterrupted production and minimizing operational risks.

The proposed framework provides a practical methodology that can be implemented within existing maintenance management systems without requiring major modifications to plant infrastructure. Maintenance engineers can apply the framework during routine maintenance planning, equipment inspections, shutdown maintenance, and asset management activities.

Furthermore, the structured maintenance assessment process facilitates improved communication among operations personnel, maintenance engineers, reliability engineers, and plant management by providing a common basis for maintenance decision-making. This integrated approach contributes to more transparent maintenance planning and supports continuous improvement initiatives.

9. CONCLUSIONS

- Proposes a structured Reliability-Centered Maintenance (RCM) assessment framework specifically for centrifugal pumps in Omani oil and gas processing plants.
- Integrates equipment functional analysis, failure mode identification, asset criticality assessment, and maintenance decision logic into a unified maintenance assessment methodology.
- Establishes a systematic maintenance task selection process that supports preventive, condition-based, and predictive maintenance strategies.
- Provides a practical engineering framework for maintenance planning and resource prioritization without relying solely on time-based maintenance schedules.
- Supports improved equipment reliability, maintenance effectiveness, and operational availability through a risk-informed maintenance approach.
- Provides a scalable methodology that can be extended to other rotating equipment, such as compressors, fans, and industrial motors.
- Creates a foundation for future implementation of IIoT-enabled condition monitoring, digital asset management, and predictive maintenance systems.

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