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An Integrated FMEA-Based Framework for Enhancing Reliability-Centered Maintenance of Centrifugal Pumps in Petrochemical Industries: A Case Study

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Abstract

Reliability-Centered Maintenance (RCM) plays a crucial role in minimizing operational downtime and lifecycle costs in petrochemical industries. However, conventional RCM approaches often lack dynamic failure diagnosis and prioritization capabilities under uncertain operating conditions. This study proposes an enhanced framework integrating Failure Mode and Effects Analysis (FMEA) with data-driven linguistic rule extraction to improve maintenance decision-making for centrifugal pumps. The proposed methodology utilizes OREDA-based failure classification to identify critical failure modes and introduces a weighted severity–occurrence model to overcome limitations of traditional Risk Priority Number (RPN) ranking. The framework establishes relationships between failure causes and key operational parameters such as flow rate, discharge pressure, vibration, temperature, and efficiency using linguistic variables. A rule-based diagnostic system is developed to enable real-time fault identification and maintenance scheduling. The framework is validated through a case study of centrifugal pumps in a petrochemical aromatic plant. Results demonstrate improved fault detection accuracy, reduced maintenance time, and enhanced system reliability. The proposed approach provides a scalable and intelligent decision-support tool for predictive maintenance and industrial asset management.

Keywords: Failure mode, FMEA, centrifugal pump, operating parameter, RCM.

INTRODUCTION

To minimize overall production expenses and enhance equipment reliability, there has been a significant focus on maintenance practices in recent years, as maintenance costs constitute a substantial portion of organizational expenditures [1]. Maintenance refers to the activities undertaken on an item to preserve it in or restore it to a designated condition. [2]. Reliability-centered maintenance (RCM) is an analytical methodology focused on enhancing component reliability to determine the preventive maintenance (PM) needs of complex systems. In numerous sectors, including aviation, steel manufacturing, and maritime, Reliability-Centered Maintenance (RCM) is recognized as the most prevalent and efficient maintenance strategy.

The objective of RCM is to reduce costs and downtime by eliminating failures. RCM encompasses two activities; the initial task involves analyzing failure modes in relation to their impact on system performance. The second aspect is the assessment of how maintenance schedules affect system reliability. To attain these objectives, all failure modes are initially discovered and classified using a failure modes and effects analysis (FMEA) Subsequently, maintenance decisions are prioritized based on the consequences and severity of the failure types [5]. Recent studies have established many ways to enhance the efficiency of reliability-centered maintenance analysis [3,4,6,7,8]. This research presents a novel framework for enhancing the RCM approach utilizing failure mode and effects analysis (FMEA). The document is structured as outlined below. Section 2 delineates the methodology of the suggested approach. In section 3, the proposed methodology is applied to the centrifugal pumps of the case study within the petrochemical industry. Section 4 encompasses the conclusion.

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METHODOLOGY

The Oil & Petrochemical industry emphasizes maintainability, reliability, and safety, employing various analyses to assess the risk of hazards and equipment damage, thereby enhancing maintenance policies and minimizing both the volume and frequency of maintenance expenditures [9]. Significant equipment malfunctions at a petrochemical facility pertain to pumps, compressors, and pipelines. Pumps of various types are utilized in every aspect of the petrochemical industry, including production, transportation, and refining. In recent years, numerous petrochemical facilities have employed sophisticated techniques to improve their comprehension of pump performance and its influence on process dynamics, thereby establishing a systematic and effective maintenance strategy [11,12].

Centrifugal pumps are utilized in various agricultural and industrial applications. Due to their diversity in types, sizes, designs, and construction materials, these pumps present a wide array of operational challenges [12]. However, the nonlinear, time-varying behavior and inaccurate measurement data of a complex system, such as a petrochemical plant, complicate the resolution of pump failures using precise mathematical equations. Diagnosing these issues requires highly experienced or educated domain experts. The failure diagnosis process conducted by human operators is time-consuming, and human mistake can result in inaccurate diagnoses, so prolonging repair times and incurring extra upgrade costs, ultimately diminishing system reliability.

This study aims to establish a novel framework for enhancing the RCM technique utilizing failure mode and effect analysis (FMEA). To attain the purpose, the critical failure modes of centrifugal pumps and their causes are first determined based on the OREDA handbook classification [13]. Subsequently, utilizing a Failure Modes and Effects Analysis (FMEA) approach informed by insights from manufacturer pump troubleshooting, field expert maintenance personnel, and the pump handbook [12], the interactive effects of these failure causes on the hydraulic and mechanical operating parameters of centrifugal pumps (e.g., flow rate, discharge pressure, vibration) are represented using linguistic variables. Subsequently, this failure information is utilized to derive language criteria for pump diagnostics, facilitating accurate and prompt assessments. Consequently, by minimizing human error and repair time, maintenance expenses are reduced; furthermore, maintenance intervals are established based on failure analysis to enhance the RCM approach. Figure 1 depicts the schematic structure of the suggested technique.

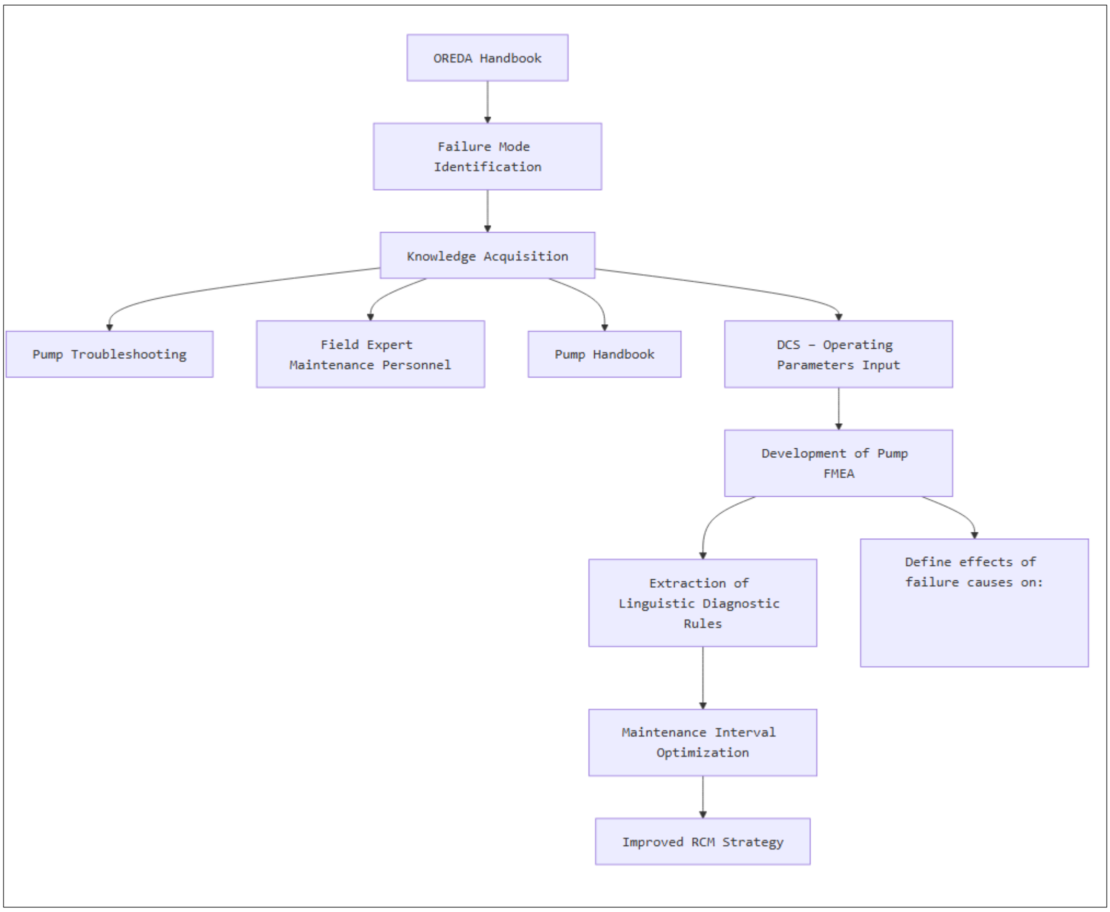
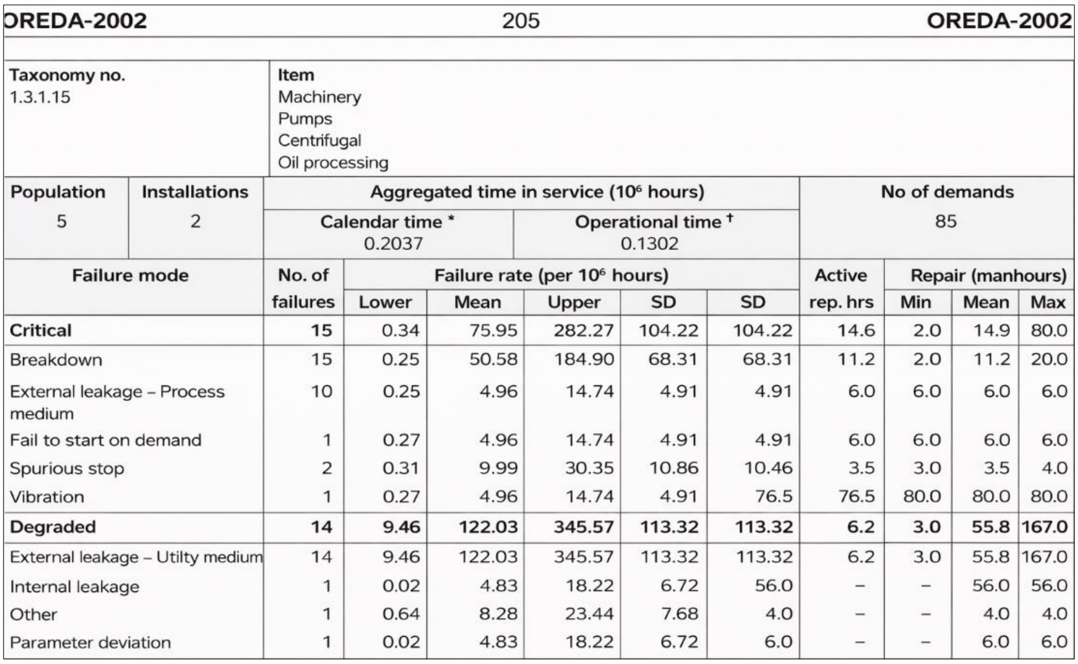


Figure 1: The schematic structure of the proposed FMEA approach for RCM improvement

OREDA classification

This study classifies equipment according to the taxonomy outlined in the OREDA (Offshore Reliability Data) handbook [13]. The OREDA handbook contains high-quality reliability data for offshore and onshore equipment, sourced from the offshore operations of ten Oil and Gas companies, and offers both quantitative and qualitative information for reliability, availability, maintenance, and safety (RAMS) analysis [13]. This taxonomy categorizes objects into equipment classes according to a primary purpose (e.g., pumps, valves). This research examines centrifugal pumps, categorized as machinery for oil processing services. This stage involves identifying the failure modes related to oil processing centrifugal pumps according to the OREDA handbook classification. The OREDA guidebook categorizes failure types by severity into four classifications: (1) severe failure, (2) degraded failure, (3) incipient failure, and (4) unknown failure [14]. This study focuses on the key failure modes with the highest failure rates among the many failure modes related with the included pump units, as outlined in the OREDA manual, without loss of generality. In the case of oil processing centrifugal pumps, the failure modes of external leakage of the process medium, spurious stops, and vibration are identified as the most prevalent critical failures, with failure rates as illustrated in Figure 2. In the subsequent phase, maintainable components of the pump related to these failure scenarios are evaluated according to the OREDA classification [13]. The failure statistics encompass the occurrence percentage of each failure mode attributable to the malfunction of each maintenance component of the oil processing centrifugal pump, as well as the occurrence percentage of each failure mode linked to each failure cause of the oil processing centrifugal pump.



OREDA-2002 205 **OREDA-2002**

Taxonomy no.	**Item**
1.3.1.15	Machinery Pumps Centrifugal Oil processing

Population	**Installations**	**Aggregated time in service (10^6 hours)**		**No of demands**
		Calendar time *	**Operational time †**	
5	2	0.2037	0.1302	85

Failure mode	**No. of failures**	**Failure rate (per 10^6 hours)**					**Active rep. hrs**	**Repair (manhours)**		
		Lower	**Mean**	**Upper**	**SD**	**SD**		**Min**	**Mean**	**Max**
Critical	**15**	0.34	75.95	282.27	104.22	104.22	14.6	2.0	14.9	80.0
Breakdown	15	0.25	50.58	184.90	68.31	68.31	11.2	2.0	11.2	20.0
External leakage – Process medium	10	0.25	4.96	14.74	4.91	4.91	6.0	6.0	6.0	6.0
Fail to start on demand	1	0.27	4.96	14.74	4.91	4.91	6.0	6.0	6.0	6.0
Spurious stop	2	0.31	9.99	30.35	10.86	10.46	3.5	3.0	3.5	4.0
Vibration	1	0.27	4.96	14.74	4.91	76.5	76.5	80.0	80.0	80.0
Degraded	**14**	**9.46**	**122.03**	**345.57**	**113.32**	**113.32**	**6.2**	**3.0**	**55.8**	**167.0**
External leakage – Utilty medium	14	9.46	122.03	345.57	113.32	113.32	6.2	3.0	55.8	167.0
Internal leakage	1	0.02	4.83	18.22	6.72	56.0	–	–	56.0	56.0
Other	1	0.64	8.28	23.44	7.68	4.0	–	–	4.0	4.0
Parameter deviation	1	0.02	4.83	18.22	6.72	6.0	–	–	6.0	6.0

Figure 2: The failure and maintenance data of the oil processing centrifugal pumps based on OREDA

Pump FMEA

Failure mode and effect analysis is one of the analytical tools by which the critical components whose failure will lead to undesirable outcomes are identified [6,16]. FMEA prioritizes the potential failure modes by developing a risk priority number (RPN) which helps managers and engineers to identify the failure modes and their cause during the design and production stages. In the RPN technique linguistic terms are used to rank the severity of the failure effect (S), the probability of occurrence of the failure mode (O), and the probability of detection of the failure mode (D) [7].

As previously mentioned, the information about the critical failure modes and the related failure causes (based on the OREDA handbook classification) are considered as inputs for the pump FMEA. The novel strategy of this study is that, through the pump FMEA the impact of failure causes on both the hydraulic & mechanical operating parameters of the pump; flow rate, discharge pressure, NPSHR (Net Positive Suction Head Required), BHP (Brake Horsepower), efficiency, vibration, and temperature, are identified.

In this stage the knowledge is acquired to complete the FMEA. To define the effects of failure causes on the hydraulic operating parameters such as flow rate & discharge pressure the knowledge is acquired as linguistic variables (variables whose values are defined in linguistic terms) from: process simulation of the plant, the pump manufacturer troubleshooting, and the field expert maintenance personnel. And to identify the effects of failure causes on the mechanical parameters such as vibration & temperature the knowledge is acquired as linguistic variables from: the pump manufacturer troubleshooting, the field expert maintenance personnel, and pump handbook [12,17]. For example, the effect of possible causes of the vibration failure mode at low flows of oil processing centrifugal pump on the hydraulic & mechanical operating parameters is depicted in Table 1. Since, the disadvantages of the RPN analysis is that RPN ranking may neglect the relative importance of the RPN elements (*S,O,*D) and as a result in some failure modes although the RPN is lower than the other failure modes, while potentially the failure mode is more dangerous [7,8], in this study, instead of the RPN number, the "weight" number is assigned to each failure cause. The weight number is the product of the (*O*) which is induced from the probability of the contribution of each failure cause and maintainable item to the failure mode, based on OREDA data, and (*S*) which is the severity of the failure cause based on the expertise of field maintenance experts. The "weight" number is scaled between 0&1 and is depicted in the last column of Table 3. Regarding the assigned weights, failure causes of each failure mode are ranked prioritized and then based on these ranks the preventive maintenance is scheduled which will increase the overall system reliability and help maintenance managers to provide suitable preventive actions.

Table 1: The pump FMEA/ In the form of linguistic variables and semiotic signs

Failure Mode	**Cause**	***Flow (Q)***	**Pressure**	***NPSHR***	***BHP***	**Efficiency**	***Velocity***	***Temp***	**Weight**
Vibration at Low Flow	Suction pipe not filled	↓↓	↓	–	–	–	↑↑	↑	**0.5**
	Insufficient NPSH	↓	–	–	↓↓	↓↓	↑↑	↑	**0.8**
	High suction specific speed	↓	↑	–	↓↓	↓↓	↑↑	–	**0.6**
	High head coefficient impeller	↓	↑↑	–	–	–	–	–	**0.5**
	Closed discharge valve operation	↓↓	↑	–	↓↓	↓↓	↑↑	↑	**0.6**
	Below minimum flow operation	↓	↓	↑	↓	↓↓	↑↑	↑	**0.9**

Furthermore, around 60 linguistic rules were derived from the pump FMEA concerning the failure modes of Leakage, Spurious Stop, and Vibration. The six diagnostic guidelines for the vibration failure mode (vibration at low flows), as outlined in Table 1, are presented in Table 2. The derived diagnostic rules will facilitate accurate and prompt identification of faults, hence minimizing repair time and human error, ultimately enhancing the system's reliability.

CASE STUDY

The equipment's being studied in this research is centrifugal pumps (with the oil processing service) of an aromatic plant of a petrochemical complex. In this section, the proposed FMEA approach is applied on a stripper column bottoms centrifugal pump with the 250*200 UCWM type. The process under study is the Sulfolane process in an Aromatic plant of a petrochemical complex. Products of the Aromatic plant are Benzene, mixed Xylenes, and Raffinates. And the Sulfolane process is used to recover high purity aromatics from hydrocarbon mixtures. In order to define the set points, the preferred, allowable, minimum & maximum operating ranges for each of the operating parameters of the pump, with regard to the P&ID of the plant (Piping and Instrumentation Diagram which defines every mechanical aspect of the plant regarding the process equipment and their interconnections), the Process Flow Diagram (PFD; which defines operating conditions, material & compositions and flow quantities) of the plant is simulated by ASPEN HYSYS (a chemical process simulation package).

Table 2: The linguistic rules for vibration failure at low flows

Rule No.	**IF (Condition)**	**THEN (Diagnosis)**
Rule 1	Q very low + Pressure low + Velocity high + Temperature high	Suction pipe not filled
Rule 2	Q very low + BHP low + Efficiency low + Velocity high + Temperature high	Insufficient NPSH
Rule 3	Q low + Pressure high + BHP low + Efficiency low + Velocity high	High suction specific speed
Rule 4	Q low + Pressure very high	Improper impeller design
Rule 5	Q very low + Pressure high + BHP low + Efficiency low + Velocity high + Temperature high	Closed discharge valve
Rule 6	Q low + Pressure low + NPSHR high + BHP low + Efficiency low + Velocity high + Temperature high	Below minimum flow

Next, based on the pump datasheet, process simulation set points, and the interpretation of the field expert maintenance personnel, the preferred, allowable, minimum, & maximum operating ranges for each of the operating parameters of the pump (flow rate, discharge pressure, NPSHR, BHP, efficiency, vibration, and temperature), are defined. For example, for the flow rate the four following ranges are defined: the [0,324.1] as very low, [324.1,370.4] as low, [370,509.3] as normal, and [509.3,545] as high.

In this stage, the operating parameters of the pump monitored by the distributed control system (DCS) are considered as the inputs for the extracted diagnostic rules. Therefore, with regard to the operating ranges of the operating parameters discussed previously, the consequence of the rules will provide the correct diagnosis of the failure. In another word, the output variable is defined as the "Failure cause".

CONCLUSION

This work delineates the nonlinear, time-varying behavior and imprecise measurement data of a pump system. Utilizing the proposed FMEA approach, the interacting effects of major pump failure modes on both hydraulic and mechanical operational parameters were identified. The suggested approach's capability to discover and classify defects, leading to accurate and prompt failure diagnosis, will enhance system reliability by optimizing equipment availability. Furthermore, the FMEA facilitates the ranking and prioritization of faults (causes of failure), enabling the scheduling of appropriate preventive maintenance actions. This analysis enhances the RCM procedure, bolsters overall system reliability, and assists maintenance managers in implementing effective preventive measures. The execution of the proposed methodology will lead to a decrease in repair duration, a minimization of human error, a reduction in unnecessary upgrade expenditures through earlier fault diagnosis, and ultimately, a decrease in maintenance costs. Additionally, the enhancement of maintenance policies will bolster the reliability and safety of the system, which is crucial in the Oil and Petrochemical industry. In subsequent research, we will use fuzzy inference to the proposed FMEA methodology to enhance rule efficacy and diminish the rule count, so yielding a more precise diagnostic system.

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