A Pump FMEA Approach to Improve Reliability Centered Maintenance Procedure: The Case of Centrifugal Pumps in Onshore Industry

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Abstract: - In the reliability centered maintenance (RCM) methodology, the reliability estimates of the system are used to provide a cost-effective & satisfactory maintenance schedule. In this paper, a new framework for improvement of the RCM procedure based on the failure mode and effect analysis (FMEA) is developed. In order to achieve the objective, first based on the OREDA handbook classification the critical failure modes of centrifugal pumps & causes of these failures are identified. Then through the FMEA, the interactive impacts of these failure causes on both hydraulic & mechanical operating parameters of the centrifugal pumps (e.g. flow rate, discharge pressure, vibration) are indicated in linguistic variables. Next, based on the obtained failure information, the linguistic rules for failure diagnosis are extracted, and moreover based on the failure analysis the maintenance intervals are determined. The ability of the proposed approach to identify and classify faults, which result in correct and timely diagnosis, will increase the reliability of the system by maximizing the equipment availability, and consequently the system performance is improved.

Keywords: - failure mode, FMEA, centrifugal pump, operating parameter, RCM

1- Introduction

In order to reduce total production costs and increase the reliability of the equipments, there has been a great concentration on maintenance policies in recent years, since maintenance costs are major costs within the organizations [1]. Maintenance defines the set of activities performed on an item to retain it in or to restore it to a specific state. [2]. Reliability centered maintenance (RCM) is one of the analytical methodologies, which is oriented to the development of component reliability to identify preventive maintenance (PM) requirements of complex systems. In many industries such as aviation, steel plant & ships, RCM is accepted as the most frequent and effective technique for maintenance [3,4].

The goal of RCM is minimization of costs and down time with regard to elimination of failures. RCM consists of two tasks; the first one is to analyze failure modes based on the effects of failures on the performance of the system. And, the second one is evaluation of the impact of maintenance schedules on the reliability of the system. In order to achieve these objectives, first all failure modes are identified and categorized through a failure modes and effects analysis (FMEA). Next, based on the consequences and severity of the failure modes maintenance decision are prioritized [5]. In the recent studies, different approaches are developed to improve the efficiency of the reliability centered maintenance analysis [3,4,6,7,8]. In this paper, a new framework for improvement of the RCM procedure based on the failure mode and effect analysis (FMEA) is developed. The paper is organized as follows. Section 2, describes the methodology of the proposed approach. In section 3, the proposed approach is implemented to centrifugal pumps of the case study (a petrochemical industry). And section 4, includes the conclusion.

2- Methodology

In the Oil & Petrochemical industry, there is a great attention on the concepts of maintainability, reliability and safety, and many analyses are used to estimate the risk of hazards and damage to equipments in order to improve maintenance policies and reduce the amount and frequency of maintenance costs [9]. The major equipment failures in a petrochemical plant are related to pumps, compressors and piping, [10]. Pumps of all types are used in every phase of petrochemical industry, production, transportation and refinery. In recent years, many petrochemical plants utilize advanced methods to enhance their knowledge and understanding about the pump performance and its impact on process behavior to provide a practical and structured approach for a satisfactory maintenance strategy [11,12].

Centrifugal pumps are used in a wide range of field & industrial applications. Since they are varied in types, sizes, designs, and materials of construction, there is a vast range of operational problems for these pumps [12]. But, due to nonlinear, time-varying behavior & imprecise measurement information of a complex system such as a petrochemical plant it is difficult to deal with pump failures with precise mathematical equations, and diagnosis of these problems needs domain experts with high experience or education. But, the failure diagnosis process by human operators is time consuming and human error may lead to a faulty diagnosis, which increases the repair time and unnecessary expenditures for upgrades and consequently the reliability of the system is decreased.

The purpose of this study is to develop a new framework for improvement of the RCM procedure based on the failure mode and effect analysis (FMEA). In order to achieve the objective, first based on the OREDA handbook classification the critical failure modes of centrifugal pumps & causes of these failures are identified [13]. Then, through a FMEA approach based on the knowledge acquisition from manufacturer pump troubleshooting, field expert maintenance personnel, and pump handbook [12], the interactive impacts of these failure causes on both hydraulic & mechanical operating parameters of the centrifugal pumps (e.g. flow rate, discharge pressure, vibration) are indicated in linguistic variables. Next, these failure information are used to extract linguistic rules for pump diagnosis, which provide correct and timely diagnosis. Consequently, by reduction of human error, reduction of repair time, maintenance costs are reduces and moreover based on the failure analysis the maintenance intervals are determined to improve the RCM methodology. The schematic structure of the proposed approach is illustrated in Figure 1.

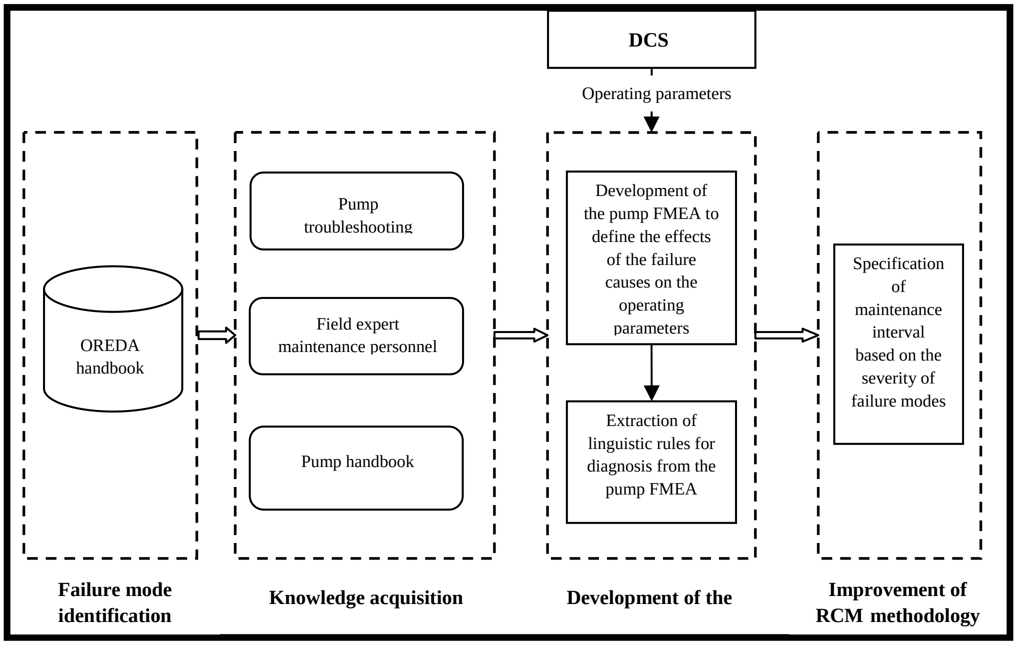

Figure 1: The schematic structure of the proposed FMEA approach for RCM improvement

2-1- OREDA classification

In this study, the equipment classification is considered based on the OREDA (Offshore Reliability Data) handbook taxonomy [13]. The OREDA handbook includes high quality reliability data for offshore/onshore equipment (which are collected from offshore equipments of ten Oil & Gas companies), and provides both quantitative and qualitative information as a basis for reliability, availability, maintenance and safety (RAMS) analysis [13]. In this taxonomy various items are classified into equipment classes based on one main function (e.g. pumps, valves). The equipments being studied in this research are centrifugal pumps, from machinery category with the oil processing service type.

In this step, the failure modes associated with oil processing centrifugal pumps based on the classification of the OREDA handbook are identified. The OREDA handbook classifies the failure modes based on their severity, in to the following four categories: (1) critical failure, (2) degraded failure, (3) incipient failure, (4) unknown failure [14]. In this study, without loss of generality, from all the different failure modes associated with the involved pump units according to OREDA handbook, the critical failure modes which have the highest failure rate are considered. For example, for the oil processing centrifugal pumps, the External leakage-process medium, the Spurious stop and Vibration failure modes, (with the 49.8, 9.82 & 4.91 failure rates, respectively), are considered as the most frequent critical failure modes, Figure 2.

In the next step, based on the OREDA classification, maintainable items of the pump associating with these failure modes are considered [13]. The failure data include the percentage of occurrence of each failure mode due to failure of each maintainable item of the oil processing centrifugal pump and the percentage of occurrence of each failure mode due to each failure cause of 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): Calendar time *	Aggregated time in service (10^6 hours): Operational time †	No of demands
5	2	0.2037	0.1302	85

Failure mode	No of failures	Failure rate (per 10^6 hours). Lower	Mean	Upper	SD	n/τ	Active rep.hrs	Repair (manhours) Min	Mean	Max
Critical	**15***	**0.34**	**75.95**	**282.27**	**104.22**	**73.62**	**14.6**	**2.0**	**14.9**	**80.0**
	15†	**0.55**	**98.46**	**351.20**	**129.75**	**115.23**				
Breakdown	1*	0.27	4.96	14.74	4.91	4.91	-	-	-	-
	1†	0.05	7.18	24.72	9.11	7.68				
External leakage - Process medium	10*	0.25	50.58	184.90	68.31	49.08	11.2	2.0	11.2	20.0
	10†	0.45	66.25	228.19	84.11	76.82				
Fail to start on demand	1*	0.27	4.96	14.74	4.91	4.91	6.0	6.0	6.0	6.0
	1†	0.05	7.18	24.72	9.11	7.68				
Spurious stop	2*	0.31	9.99	30.35	10.46	9.82	3.5	3.0	3.5	4.0
	2†	2.28	14.56	35.69	10.86	15.36				
Vibration	1*	0.27	4.96	14.74	4.91	4.91	76.5	80.0	80.0	80.0
	1†	0.05	7.18	24.72	9.11	7.68				
Degraded	**14***	**13.79**	**67.80**	**155.57**	**45.52**	**68.72**	**6.2**	**3.0**	**48.6**	**167.0**
	14†	**9.46**	**122.03**	**345.75**	**113.32**	**107.55**				
External leakage - Utility medium	11*	22.62	53.63	95.34	22.57	53.99	6.2	3.0	55.8	167.0
	11†	13.55	93.14	232.30	71.41	84.50				
Internal leakage	1*	0.02	4.83	18.22	6.72	4.91	-	56.0	56.0	56.0
	1†	0.64	8.28	23.44	7.68	7.68				
Other	1*	0.02	4.83	18.22	6.72	4.91	-	4.0	4.0	4.0
	1†	0.64	8.28	23.44	7.68	7.68				
Parameter deviation	1*	0.02	4.83	18.22	6.72	4.91	-	6.0	6.0	6.0

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

2-2- 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 prioritize 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 Horse Power), 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. With regard to 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	**Possible cause of the failure:**	**Q** (m^3/hr)	**Disch. Press.** (kg/cm^2)	**NPSHR** (*m*)	**BHP** (*kW*)	**Efficiency** (%)	**Velocity** (mm/s)	**Temp.** (°C)	**Weight**
Pump vibration at low flows	1. Pump suction pipe not completely filled with liquid	Decrease (--)	Decrease (-)	-	-	-	Increase (++)	Increase (+)	0.5
	2. Insufficient available NPSH	Decrease (-)	-	-	Decrease (--)	Decrease (--)	Increase (++)	Increase (+)	0.8
	3. Selection of pump with too high a suction specific speed	Decrease (-)	Increase (+)	-	Decrease (--)	Decrease (--)	Increase (++)	-	0.6
	4. Impeller selection with abnormally high head coefficient	Decrease (-)	Increase (++)	-	-	-	-	-	0.5
	5. Running the pump against a closed discharge valve without opening a by-pass	Decrease (--)	Increase (+)	-	Decrease (--)	Decrease (--)	Increase (++)	Increase (+)	0.6
	6. Operating pump below recommended minimum flow	Decrease (-)	Decrease (-)	increase	Decrease (-)	Decrease (--)	Increase (++)	Increase (+)	0.9

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

Rule No.	If (premise)	Then (consequent)
Rule 1.	Q is very low & Disch. Press. is low & Velocity is very high & Temperature is high	Pump suction pipe not completely filled with liquid
Rule 2.	Q is very low & BHP is very low & Efficiency is very low & Velocity is very high & Temperature is high	Insufficient available NPSH
Rule 3.	Q is low & Disch. Press. is high & BHP is low & Efficiency is very low & Velocity is very high	Selection of pump with too high a suction specific speed
Rule 4.	Q is low & Disch. Press. is very high,	Impeller selection with abnormally high head coefficient
Rule 5.	Q is very low & Disch. Press. is high & BHP is very low & Efficiency is very low & Velocity is very high & Temperature is high	Running the pump against a closed discharge valve without opening a by-pass
Rule 6.	Q is low & Disch. Press. is low & NPSHR is high & BHP is low & Efficiency is very low & Velocity is very high & Temperature is high	Operating pump below recommended minimum flow

Moreover, based on the pump FMEA for the Leakage, Spurious stop and Vibration failure modes, about 60 linguistic rules were extracted. For example, the six diagnostic rules for the Vibration failure mode (vibration at low flows) based on the Table 1, are depicted in Table 2. The extracted diagnostic rules will provide correct and timely diagnosis of the failures, which by reduction of repair time & human error will increase the reliability of the system.

3- Case study

The equipments being studied in this research are 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 C_5+ Raffainate. 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).

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”.

4- Conclusion

In this paper, due to nonlinear, time-varying behavior & imprecise measurement information of a pump system, through the proposed FMEA approach the interactive impact of the critical pump failure modes on the both hydraulic & mechanical operating parameters was specified. The ability of the proposed approach to identify and classify faults, which result in correct and timely failure diagnosis, will increase the reliability of the system by maximizing the equipment availability. Moreover based on the FMEA, faults (failure causes) are ranked and prioritized and with regard to this analysis, the appropriate preventive maintenance actions can be scheduled to improve the RCM procedure and increase the overall system reliability and help maintenance managers to provide suitable preventive actions. The implementation of the proposed approach would result in reduction of repair time, reduction of human error, reduction of unnecessary expenditures for upgrades by providing the earlier diagnosis of the faults and finally by reduction of maintenance costs and improvement of maintenance policies will increase the reliability & safety of the system, which plays an important role in the Oil & Petrochemical industry. In the further studies, we are to implement fuzzy inference on the proposed FMEA approach, in order to improve the effectiveness of rules and reduce the number of rules to provide a more accurate diagnostic system.

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