An Improvement of Maintenance Scheduling for Rotating Equipment Based on the Estimated Risk-Based Inspection Approach

Abdelnaser Elwerfalli
Mechanical Engineerin Dept
College of Mechanical Engineerin Technology
Benghazi - Libya
gq7qg@yahoo.com

Ashraf Wanis
Mechanical Engineerin Dept
College of Mechanical Engineerin Technology
Benghazi - Libya
ashraf91082@gmail.com

Hweda Sharif
Aircraft Maintenance Engineer in Dept
Technical College of Civil Aviation and Meteorology
Esbea - Libya
Hwedasharif@gmail.com

***Abstract*— The importance of maintenance scheduling has increased due to its high cost and role in reducing the risk, that contributes in enhancing the safety requirements and reduce the production losses in order to increase the operation periods for any processing plant. Therefore, selection of the Estimated Risk-Based Inspection (ERBI) approach considers one of the most important decision making tools for scheduling maintenance activities at any processing plant run under the hard operating conditions. Any a processing plant consists of several rotating equipment pieces that operated continuously under the random conditions due to the common failures. The study highlighted on failures of centrifugal pumps listed at the inspection and maintenance records for refinery plant. As most processing plants implemented maintenance program based on the recommendations of Original Equipment Manufacturers (OEMs). These recommendations may be perfect suggestion on the short term. However, they cannot be feasible on the long term due to the operating conditions and the production requirements for any a processing facility. Therefore, the present study aimed at improving maintenance scheduling for rotating equipment using the Estimated Risk-Based Inspection approach. This approach is characterized as a tool to decrease maintenance costs, mitigate consequences, minimize downtimes, and reduce production losses. The results of Estimated Risk-Based Inspection application showed that the maintenance scheduling could improve and apply in other industrial environments to prolong equipment life and optimize all aspects related to the reliability, availability, and maintainability.**

Keywords—maintenance, centrifugal pumps estimated risk-based inspection, reliability analysis.

I. Introduction

Maintenance is a set of activities that performed on equipment to keep or restore it to the normal state with aiming an increase in the operating life [1]. Maintenance is the major activity for any processing plant run under the harsh conditions such as a gas, oil, refinery and petrochemical plants. Maintenance activities are expensive in terms of cost and production losses due to downtime of plant or planned shutdown. In order to reduce maintenance costs and decrease production losses, there has been a great concentration on the maintenance activities in recent years, because maintenance costs have become major event within any plant. The reducing costs of maintenance can be achieved by scheduling maintenance and inspection activities based on the rotating equipment. Centrifugal Pumps (CPs) is one of rotating equipment pieces that takes into consideration in the study for identifying and quantifying degradation mechanisms and risk in order to help the practitioners in scheduling maintenance activities. Refinery plant at the Sirte Oil Company (SOC) is a good example, which can be considered as a worst case study for Libyan refineries due to a number of reasons including the geographical location, technical aspects, and operational conditions. The refinery plant consists of many types of rotating equipment such as compressors, pumps, turbines, and helper motors.

Maintenance interval is a periodically shutdown of a plant, once a year or every two years or more, this depends on the age of plant, size, the type of systems, the status of the equipment, financial situation of the company, risks level, reliability and efficiency of the plant as well [2]. Halib et al. [3] identify 15 plants. refinery plant is one of plants that highlights to determine maintenance scheduling, once e every five years. However, Obiajunwa [4] states that maintenance scheduling sometimes is very difficult to estimate. Lawrence [5] states that most processing plants that operate continuously under severe conditions should shut down their facilities every few years to achieve maintenance requirements. most the suggested intervals were not represented optimum time to maintenance strategy due to operating conditions that may vary significantly from company to another. Swart [6] reports that historically, intervals of maintenance determine without any real strategy associated with operating process.

The motivations for applying Risk-Based Inspection (RBI) approach has become increasingly important to prolong a life of equipment/unit and to avoid an unexpected risk due to hazard material and complex process [7]. The maintenance scheduling of rotating equipment often determines by Original Equipment Manufacturers (OEMs) recommendations. However, OEMs recommendations may be a perfect suggestion only on the short term. However, OEMs suggestion can not be feasible on the long term due to operating conditions and process configurations for any facility, especially that run under the harsh operating conditions [2]. On the long term, many processing plants set interval and cost of maintenance without any real strategy plan associated with operating risks. This means that strategy of maintenance identifies the interval time and cost of maintenance randomly and permanently. Therefore, this paper designs to improve maintenance scheduling using Estimated Risk-Based Inspection (ERBI) based on the maintenance records associated with rotating equipment pieces to decrease maintenance costs, mitigate consequences, minimize downtimes and optimize all the reliability aspects.

II. ESTIMATED RISK-BASED INSPECTION (ERBI) METHODOLOGY

The ERBI methodology proposes in the present work is a quantitative approach to determine interval of plant shutdown. This methodology presents an optimal time of maintenance interval with taking the overall system availability, reliability and risk into consideration. The ERBI proposes to improve maintenance scheduling of a planned shutdown for any plant and maintain a high level of pumps availability with considering the critical pumps from the risk perspective and ensuring that the overall financial impact is kept to a minimum in order to achieve better results with less operating expenses.

In this study, a methodology is to estimate RBI in determining interval of maintenance is presented. This methodology can be broken down into many steps, as shown in Fig 1:

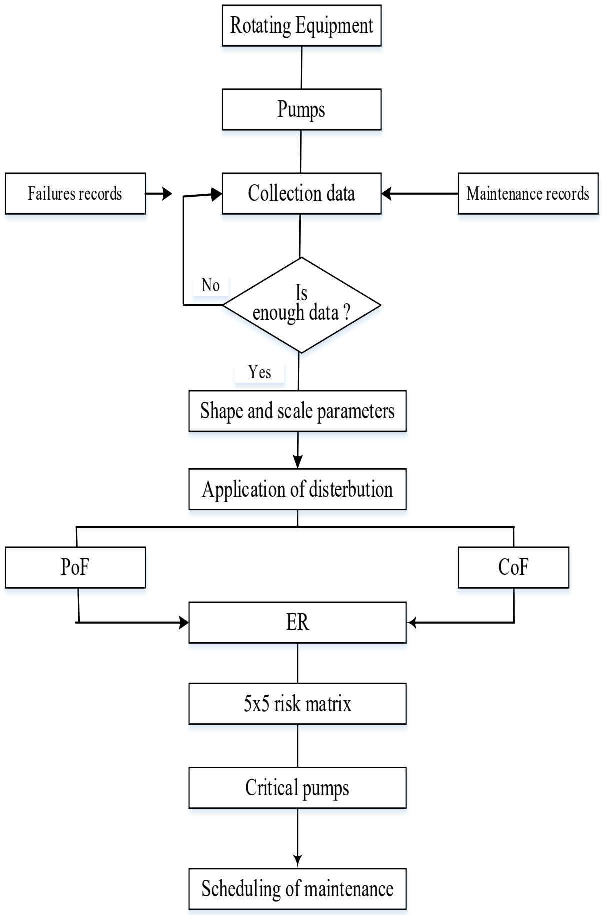


Fig 1. Estimated risk-based inspection Methodology

- Data collection associate with CPs failures according to the maintenance records at refinery plant,
- Determination of reliability function based on the shape and scale parameters, which can extract by the failures analysis,
- Distribution of pumps on the 5x5 risk matrix based on the Probability of Failure (PoF) and Consequences of Failure (CoF) resulting from the safety records,
- Selection of the pumps locating in the high risk level as the critical rotating equipment.
- determination of maintenance scheduling as an optimum time of maintenance interval.

III. FAILURE ANALYSIS OF CENTRIFUGAL PUMPS (CPS

Centrifugal pumps (CPs) consists of hundreds of components no matter how big or tiny. However, some main components represent critical parts of CPs to avoid any threat related to specific functions of the system. The main components can be shown in Fig 2:

- Mechanical seal (Packing rings) uses to prevent the leakage of liquid into the surroundings.
- Bearing aims at supporting the weight of shaft to carry the hydraulic loads acting on the shaft, and

keep the pump shaft aligned to the shaft of the driver.

- Shaft in a centrifugal pump contributes at transmitting the input power from the driver into the impeller.
- Impeller uses as a primary source for pumping action in order to increase the liquid pressure.
- Coupling is to connect the pump shaft with the driver shaft to transmit the power from the driver to the pump.
- Casing is a pressure containment vessel that contains the liquid to direct the flow of liquid in and out of the centrifugal pump.

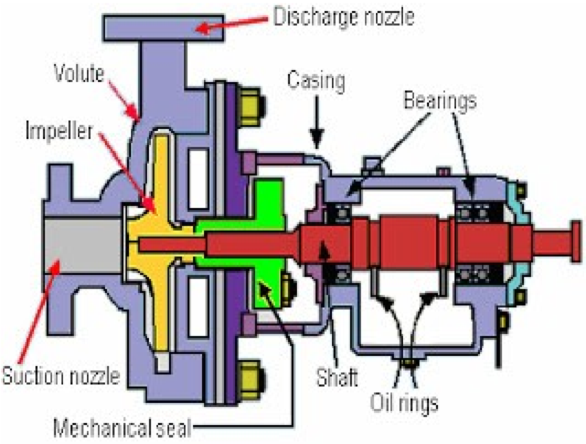


Fig 2. Main failures of CPs

CPs is considered part of critical equipment that can effect on the entire production and manufacturing process chain [8]. CPs are considered sensitive equipment due to several factors: fluctuating temperatures (M1), over pressures (M2), volume of fluid (M3) maintenance-related problems (M4) as shown in Fig 3. These factors can affect directly on the required performance of CPs, and can also be a reason in generating mechanical and electrical failures.

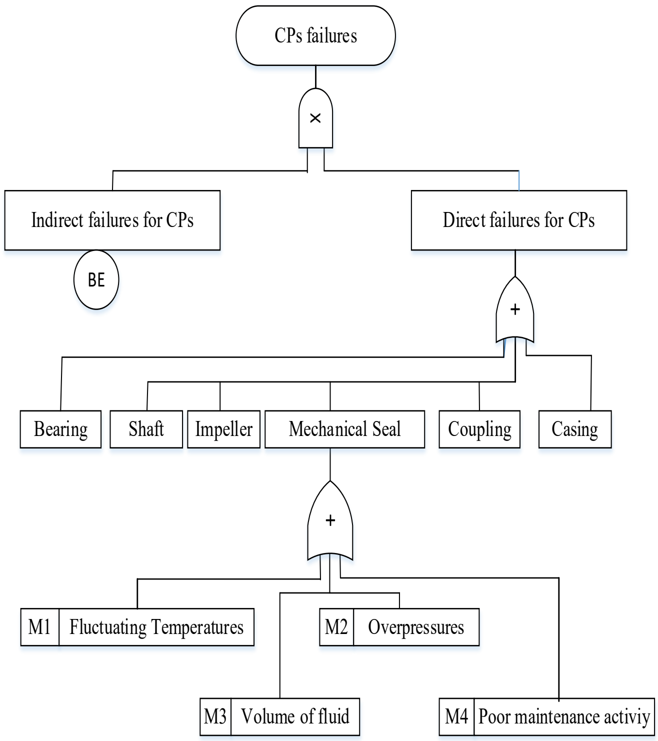


Fig 3 Fault Tree Analysis (FTA) for CP failures

From a risk point of view and based on the inspection and maintenance records, a critical failure of CP that should be taken into account is mechanical seal, due to a leakage of chemical fluid to the atmosphere can be dangerous resulting from variable operational conditions such as over pressures, fluctuating temperatures and poor in the maintenance strategy. For this reason, reliability of mechanical seal in the pumps is one of vital aspects for the process to avoid any threat related to production losses and environment damage into the surroundings.

IV. Prepare Estimated Risk –Based Inspection of CPs

ERBI is very crucial step in the decision making to determine likelihood and consequences of failure. Risk assessment aims to estimate probability of failure and their consequences, which can be qualitative or quantitative [9]. ERBI can be calculated as the product for each probability and consequence of failure scenario, the risk of system being the total of all the risk scenarios.

ERBI is the sum of all the risks associated with the possible consequences scenarios in the operational and technical failures resulted from the proposed FTA. Therefore, ERBI associates with the financial risk can be expressed by Equation 1 [10]:

$$ERBI = [PoF_1 \;\; PoF_2 \ldots PoF_n] \times \begin{bmatrix} CoF_1 \\ CoF_2 \\ CoF_n \end{bmatrix} \tag{1}$$

$$PoF(t)_i = 1 - R(t)_i \tag{2}$$

Where: R(t): Reliability function and t: interval time (hr.).

Acceptance Risk (AR): In general, AR varies from a company to another due to the operating conditions and economic aspects. Based on the economic aspects, every processing plant has its own AR criteria, can be used in estimating the maintenance scheduling according to the RBI [11]. AR criterion for CPs at plant is estimated to be equal or less than 300 $/h. Therefore, ER must be equal or less than AR to achieve tasks of maintenance scheduling without any threat.

$$\text{ERBI} \leq \text{Acceptance Risk (AR)} \quad (3)$$

The Exceptional and Weibull models are widely used because it has a great variety of shapes which enables it to fit many kinds of data, especially data relating to product life. The Exceptional and Weibull models are applied to determine the failure behavior of the mechanical seal during the random life of equipment.

Three parameters; failure rate (λ), shape (β) and scale (η) contribute in identifying the appropriate model according to the failures records. Shape parameter (β) uses to define the shape of this distribution and η is the scale parameter that defines the spread of distribution, for instance β = 1 means that failure rate is a constant and the component is failing, and if β > 1 means that the analyzed component is failing due to wear-out and a scheduled maintenance is justified.

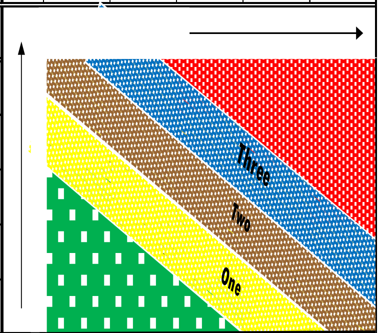
$$R(t) = \begin{cases} \text{Exp}^{-\lambda t} & \text{Exceptional model} \quad \beta = 1 \\ \text{Exp}^{-\left(\frac{t}{\eta}\right)^{\beta}} & \text{Weibull model} \quad \beta > 1 \end{cases} \quad (4)$$

V. Results and Discussion

Table 1 shows 5x5 risk matrix for six CPs that distribute based on PoF and CoF (related to Production Losses "PL" and Environment Damage "ED". Six pieces of pumps are located in the very low risk. One piece of pumps is rated in the low risk zone. Two of CPs are rated in the moderate risk zone, and three pieces of CPs are classified in the high risk zone. As a result, three CPs are only located in the high risk zone must be taken into consideration to consider the scheduling of maintenance. These CPs are considered critical equipment pieces.

Table 1. the 5x5 risk matrix for six pieces of CPs

Consequnces / Likelihood				ED	No effect	Minor	Moderate	Major	Massive
				PL	Less 20 %	20 – 40 %	40 - 60 %	60 - 80 %	More 80 %
				COF	1	2	3	4	5
Failure Level	Range / Mth	P(t)	POF						
Frequent	t > 6 (Mths)	1	5						
Likely	4 < t ≤ 6	0.75	4						
Possible	2 < t ≤ 4	0.5	3						
Unlikely	1 < t ≤ 2	0.25	2						
Rare	≤ 1	0.1	1						
Key for Ranking	Risk Ranking				R ≤ 3	3 < R ≤ 6	6 < R ≤ 9	9 < R ≤ 12	R > 12
	Risk Catogery				V. Low	Low	Moderate	High	V. High
	Risk Level								



In order to run continuously and safely of the plant, it means that two-out-of-three (2oo3) pumps at least must be operated to avoid any an unexpected failure and improve the reliability of system as well. Therefore, the reliability function of plant can be expressed as the following Equations:

$$R_{system} = R(t)_A\, R(t)_B\, R(t)_C + PoF(t)_A\, R(t)_B\, R(t)_C + R(t)_A\, PoF(t)_B\, R(t)_C + R(t)_A\, R(t)_B\, PoF(t)_C \quad (5)$$

If $R(t)_A = R(t)_B = R(t)_C = R(t)$

then $PoF(t)_A = PoF(t)_B = PoF(t)_C = PoF(t)$

So; $R(t)_{2oo3} = R(t)^3 + 3\,R(t)^2 .PoF(t)$

$$R(t)_{2oo3} = 3R(t)^2 - 2R(t)^3 \quad (6)$$

Fig 4 represents Reliability Block Diagram (RBD) that describes the redundancy configuration of reliability function R(t) of 2oo3 system under success logic.

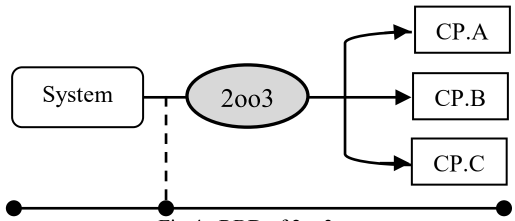


Fig 4. RBD of 2oo3 system

From the failure data analysis performed on mechanical seal for three CPs. Based on the SPSS technique, it finds that shape (β) and scale (η) parameters for three CPs as the following Table 2:

Table 2. Shape and scale parameters for critical CPS

Equipment	β	η (hr.)	R(t)	R(t)
CP. A	1,15	6513		$\text{Exp}^{-\left(\frac{t}{6513}\right)^{1.15}}$
CP. B	1.37	4871		$\text{Exp}^{-\left(\frac{t}{4871}\right)^{1.37}}$
CP. C	1,24	5775		$\text{Exp}^{-\left(\frac{t}{5775}\right)^{1.24}}$

Table 3 shows the results related to the reliability function R(t), PoF(t) and CoF of (2oo3) system during the operational periods (t) of CPs. It is evident from table 3 that by estimating PoF(t) and CoF according to the operation and safety records for CPs, ERBI (per hour) will be significantly increased with increasing in the operation time of the 2oo3 system until ERBI reaches to the highest peak at 282, then decreased as shown in Fig 4.

Table 3. R(t), PoF(t), and ERBI results of the 2oo3 system

t (hr)	R(t) System	PoF(t) System	ERBI	ERBI Per hr
720	0.941	0.0589	104383	145
1440	0.816	0.1832	324409	225
2160	0.676	0.3238	573221	265
2880	0.542	0.4570	808967	281

3600	0.426	0.573	1014296	282
4320	0.330	0.669	1184630	274
5040	0.253	0.746	1321577	262
5669	0.199	0.800	1417163	250
5758	0.192	0.807	1429078	248
6480	0.145	0.854	1512848	233
7200	0.109	0.890	1576829	219
7920	0.081	0.918	1625434	205
8640	0.060	0.939	1662119	192
9360	0.0454	0.954	1689671	181

* CoF = $1,770,000

As a result, higher numbers of operation periods are needed of the 2oo3 system. From the above results, the 2oo3 system should be under the normal operation to 3600 hours, and then must be stopped it to implement maintenance activities. This means that the system must be shut down every 3600 hrs. when ERBI is rated in the high risk zone at 282 to avoid a jump to the very high risk zone and reduce any threat may effect on the operation stability.

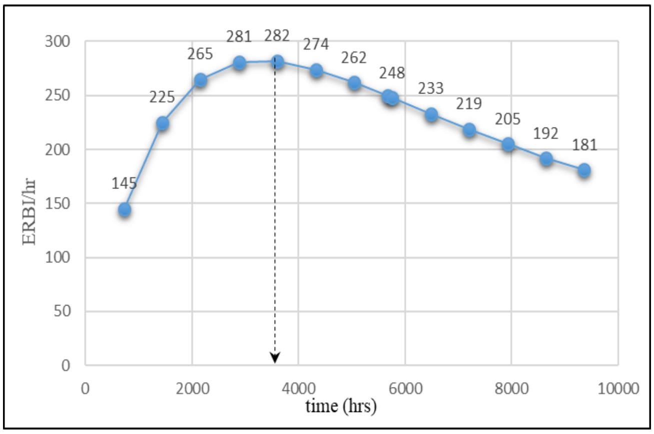


Fig 4. The highest risk based on the ERBI

VI. VALIDATION OF RESULTS

There are many approaches that would be able to determine maintenance interval. However, it is very rare obtain particular application has been used in any a processing plant to estimate maintenance scheduling. As a result, most processing plants used traditional techniques to estimate maintenance scheduling based on the predetermined time and fixed budget (once every a few years) to become maintenance scheduling as a normal routine. This means that most processing plants did not take critical equipment pieces into consideration for scheduling maintenance event.

ERBI methodology is validated based on the accumulated fouling in the heat exchangers for methanol plant / SOC. In 2019, the methanol plant required more attention for improving maintenance scheduling to execute every 26,280 hrs rather than 17,520 hrs in 2018 based on the critical static equipment. In addition, the refinery plant at SOC was a good example to validate the study. The plant consists of many rotating equipment pieces. The implementation of Preventive Maintenance (PM) for all rotating equipment pieces were randomized at the same time every 4320 hrs. Based on the ERBI methodology that PM can be executed every 3600hrs to avoid any threat related to the production losses. The methodology achieved results close to the actual status of maintenance interval for heat exchangers. Therefore, the ERBI methodology has become a tool in order to obtain tangible optimizations of maintenance scheduling for any equipment run under harsh operating conditions.

VII. CONCLUSIONS

The purpose of the study was to improve maintenance scheduling for any a processing plant that run continuously under harsh operational conditions based on the CPs. In this study was used the estimated Risk-Based Inspection approach to assess risk due to mechanical seal failures for a set of CPs equipment.

All of approximately six CPs in area were assessed in the refinery plant and distributed on the 5x5 risk matrix. therefore, it found that there three pieces were rated in the high risk zone (critical PCs equipment). Based on the Weibull model, R(t) of 2oo3 system and PoF(t) were calculated to identify ERBI every operation time. Every 3600hrs was the optimal time scheduling to execute maintenance event according to risk indicator associated with rotating equipment. The results showed that maintenance scheduling could be executed every 3600hrs with prolonging equipment life, and optimizing all aspects related to reliability, availability, and maintainability.

Analysis showed that ERBI application of rotating equipment had the ability to improve the maintenance scheduling without any an increasing in risk or threat to associated with operating system of plant. Therefore, ERBI approach can also be able to apply in other industrial environments in order to improve maintenance scheduling.

REFERENCES

[1] Elwerfalli A. and Al-Maqespi S. (2021) Selection of Appropriate Maintenance Strategy for Oil and Gas Equipment Using Analytical Hierarchy Process (AHP), Proceedings of the International Conference on Industrial Engineering and Operations Management Sao Paulo, Brazil.

[2] Emiris, D. (2014) ‘Organizational context approach in the establishment of a PMO for turnaround projects, experiences from the Oil and Gas industry’, *PM World Journal*, 3(2), pp. 1-15.

[3] Halib, M., Ghazali, Z. and Nordin, S. (2010) *Plant Turnaround Maintenance in Malaysian Petrochemical Industries*: A study on Organizational size and structuring processes, 9.

[4] Obiajunwa, C. (2012) 'A framework for the evaluation of turnaround maintenance projects'. *Journal of Quality in Maintenance Engineering*, 18(4), pp.368-383.

[5] Lawrence, G. (2012) *Cost estimating for turnarounds*, Petroleum Technology Quarterly, *17*(1), 33.

[6] Swart, P. (2015) An Asset Investment Decision Framework to Prioritise Shutdown Maintenance Tasks, MSc thesis, University of Stellenbosch.

[7] Hameed, A. and Khan, F. (2014) 'A framework to estimate the risk-based shutdown interval for a process plant', *Journal of Loss Prevention in the Process Industries,* 32, pp. 18-29.

[8] Lihovd E, Johannessen T, Steinebach C, and Rasmussen, M. (1998) "Intel□ligent diagnosis and maintenance management," Journal of Intelligent Manufacturing, vol. 9, pp. 523–537.

[9] Arendt, S. (1990) 'Using quantitative risk assessment in the chemical process industry', Reliability. Eng. System. Safety, 29, pp.133–149.

[10] Elwerfalli, A.; Alsadaie, S.; Mujtaba, I.M. Estimation of Shutdown Schedule to Remove Fouling Layers of Heat Exchangers Using Risk-Based Inspection (RBI). *Processes* **2021**, *9*, 2177. https://doi.org/10.3390/pr9122177.

[11] American Petroleum Institute (2008) Risk Based Inspection; 2nd ed., Washington, DC, USA: API publication 581.