# A STRUCTURED RELIABILITY AND MAINTAINABILITY ASSESSMENT MODEL: AN APPLICATION TO HIGH VOLTAGE MOTORS

Majdi M. Obaid[1] and Qadeer Ahmed[2, *]
[1]Shedgum Gas Plant, Saudi Aramco, Shedgum, Saudi Arabia
[2]Consulting Services Department, Saudi Aramco, Dhahran, Saudi Arabia

**Abstract:** Motors are one of the vital equipment and generally the higher in numbers in oil and gas processing facilities. The primary function is to drive the process equipment such as compressors, fans, pumps etc. Unreliability of the motors is a threat to safety but also to production loss and high operating expenditure. Motors experience higher failure rates and maintenance costs with age due to lower focus during useful life periods. In order to properly address the long-term reliability and maintainability of the motors and associated subsystems, this paper aims to propose a structured methodology and set of tools to ensure effective assessment. The proposed model mainly consists of data collection, analysis, assessment, financial analysis and later developed actions to properly address the concerns. Equipment failure and repair data is a challenge to any reliability assessment; hence, proposed methodology was introduced to collect, verify and validate the data. Later, multiple tools such as Pareto Analysis, Failure Mode and Effect Analysis and Root Cause Analysis were used to perform a detailed assessment. Weibull analysis was also explored to understand the failure modes, which ultimately helped in improving the availability of the motors. The proposed methodology has been applied to high-voltage motors to observe the effectiveness of the tools and proposed model in addressing reliability and maintainability. The results show significant reliability improvements of 12% (from 58% to 70%) and prove that the structured method can be effectively used in complex process facilities with significant benefits.

***Keywords:*** Reliability; Maintainability; Data Analysis; Failure Modes & Effect Analysis; Weibull Analysis; Root Cause Analysis.

# نموذج تقييم هيكلي للموثوقية والقدرة على الاستدامة: تطبيق على المحركات عالية الجهد

مجدي محمد العبيد وقدير أحمد

**الملخص:** تعد المحركات أحد المعدات الحيوية تتزايد أعدادها بشكل عام في منشآت معالجة النفط والغاز، وتتمثل وظيفتها الأساسية في قيادة معدات المعالجة مثل الضواغط والمراوح والمضخات وما إلى ذلك. إن عدم موثوقية المحركات يمثل تهديدًا للسلامة، ولكن أيضًا لخسارة الإنتاج ونفقات التشغيل المرتفعة. تواجه المحركات معدلات أعطال أعلى وتكاليف صيانة أعلى مع تقدم العمر بسبب انخفاض التركيز خلال فترات العمر الإنتاجي. من أجل معالجة الموثوقية طويلة المدى وقابلية الصيانة للمحركات والأنظمة الفرعية، تهدف هذه الورقة إلى اقتراح منهجية منظمة ومجموعة من الأدوات لضمان التقييم الفعال. يتكون النموذج المقترح بشكل أساسي من جمع البيانات والتحليل والتقييم والتحليل المالي والإجراءات التي تم تطويرها لاحقًا لمعالجة المخاوف بشكل صحيح. يمثل فشل المعدات وبيانات الإصلاح تحديًا لأي تقييم موثوقية، لذلك تم تقديم المنهجية المقترحة لجمع البيانات والتحقق منها والتحقق من صحتها. تم بعد ذلك استخدام أدوات متعددة مثل تحليل باريتو ووضع الفشل وتحليل التأثير وتحليل السبب الجذري لإجراء تقييم مفصل. تم استكشاف تحليل ويبل أيضًا لفهم أوضاع الفشل، والتي ساعدت في النهاية في تحسين توافر المحركات. تم تطبيق المنهجية المقترحة على المحركات عالية الجهد لمراقبة فعالية الأدوات والنموذج المقترح في معالجة الموثوقية وقابلية الصيانة. تظهر النتائج تحسينات كبيرة في الموثوقية بنسبة 12٪ (من 58٪ إلى 70٪) وتثبت أن الطريقة المنظمة يمكن استخدامها بشكل فعال في مرافق العمليات المعقدة مع فوائد كبيرة.

***الكلمات المفتاحية:*** الموثوقية؛ قابلية الصيانة؛ تحليل البيانات؛ أوضاع الفشل وتحليل التأثير؛ تحليل ويبل؛ تحليل السبب الجذري.

Corresponding author's e-mail: dr.qahmed50@gmail.com

DOI:10.53540/tjer.vol19iss2pp152-162

## NOMENCLATURE

| | |
|---|---|
| AC | Alternating Current |
| CBM | Condition-Based Maintenance |
| CoU | Cost of Unreliability |
| DC | Direct Current |
| FMEA | Failure Mode and Effect Analysis |
| FTA | Fault Tree Analysis |
| HAZOP | Hazard and Operability |
| HVM | High Voltage Motors |
| MTBF | Mean Time Between Failures |
| MTTR | Mean Time to Repair |
| PoF | Probability of Failure |
| RAAM | Reliability Assessment and Analysis Model |
| RCA | Root Cause Analysis |
| SEM | Submersible Electric Motor |

## 1. INTRODUCTION

Reliable operations of High Voltage Motors (HVM) are vital to ensure the overall availability and safe operation of the facility. Due to its criticality, it has become an ever-increasingly main topic and equipment in the organizational continuous improvement toolbox. Higher plant reliability helps to reduce operating costs as asset failure causes a reduction in production output and high maintenance cost, which in turn limits profitability. Additionally, equipment failures increase the probability of an environmental incident and the potential for safety-related accidents. The motor is one of the highest numbers of equipment in any oil and gas facility. Based on the design requirements, a proper motor, such as an induction or synchronous motor, is selected to perform its function. In the oil and gas industry, motors are generally used as drivers to many driven equipment such as pumps, compressors, heat exchangers, coolers and other rotating equipment, as shown in Figure 1. Gas plants are one of the key facilities in the oil and gas industry, and the high availability of these facilities is essential to both revenue generation and safe operations. The purpose of the gas plant is to recover the Natural Gas Liquid (NGL) from a gas such as ethane, butane, propane, and gasoline from gas. The gas plant is equipped with many rotating equipment, such as compressors, turbines, pumps, and gearboxes. One of the critical rotating equipment systems is propane refrigeration. It is a closed-loop system and is critical to gas plants. The refrigeration system has compressors driven by motors. In this system, two three-stage propane compressors driven by a 21,000 hp motor in parallel are fed from three suction scrubbers. These high-voltage motors are used as a case study in this paper.

To ensure the high availability of the high voltage motors, a structured methodology is developed and utilized to perform the assessment. This assessment is based on the maintenance downtime and time to failure data and associated maintenance cost for a set of motors. The details are discussed in the later part of the paper.

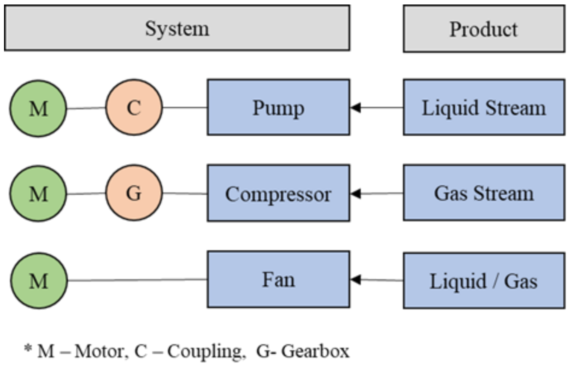


**Figure 1.** General Motor Applications and Setup.

The remaining paper is structured as follows: Section (2) outlines the literature review to understand the methodologies researcher have used to improve the reliability and availability of high-voltage motors. Section (3) presents the methodology to perform this analysis, the analysis and the tools used to address the poor reliability of the motors. Section (4) presents the assessment recommendation, and finally, conclusions are discussed in section (5).

## 2. LITERATURE REVIEW

Due to its importance and its wide applications in industry, motor reliability is a topic of interest for both academia and industry. Motors are commonly used as a driver of many assets, such as pumps, compressors and fans. Being vital equipment in oil and gas processing facilities, the unreliability of the motors is a very critical and significant threat to safety, production loss and operating expenditure. Due to its importance, many companies have developed tools, technologies and develop applications to assess motor conditions.

Proper maintenance is important to ensure the reliability and availability of motors. Maintenance of these large motors is proposed using a three-pronged approach Edwin and Syam (2010). In this work, the motor is considered as a system and split into four subsystems individually, and later the results are combined with observing the overall outcome. Later, Failure Mode and Effect Analysis (FMEA), Hazard and Operability (HAZOP) and Fault Tree Analysis (FTA) are simultaneously applied to these subsystems to identify their failure modes. In the end, using a condition indicator for each of these failure modes, failures are mitigated by using the warning signals received while monitoring the condition parameters. A statistical analysis of the operation of motors and the current measurement of certain parameters of its operation to online detect the condition of electric motors is developed by Zaiets and Kondratenko (2019). A genetic algorithm is used in the optimization of the number of incoming parameters with various combinations. A neural network is also introduced for predicting the reliability of an electric motor which allows real-time detection of defects and monitoring of the condition of machines. A reliability metric is introduced based on statistical laws superposition of Mean Time Between Failures (MTBF) of submersible electric motors against surges Ilya et al. (2016). The outcome and results are presented in the form of an electric motor survival probability dynamic pattern as a function of resource consumption to protect submersible electric motors against surges. Operational and maintenance cost reduction of Induction Motors (IMs) is discussed in Choudhary et al. (2019). Costs can be better managed and reduced when the equipment is monitored regularly. Monitoring helps early detection of the deterioration of motor health, improvement in proactive response, and minimizing unscheduled downtime. Condition-Based Maintenance (CBM) is an effective method to maintain assets. A CBM strategy for continuously monitored degrading systems with multiple failure modes is presented by Liu, Xiao, et al. (2013). Unlike existing CBM models, this article considers multiple sudden failures that can occur during a system's degradation, and the failure rate corresponding to each failure mode is influenced by either the age of the system. A statistically dependent model is developed considering time-to-maintenance due to system degradation and time-to-failure of different failure modes. An optimum maintenance threshold level is achieved that maximizes the system's availability over its life cycle.

An Analytical Hierarchical Process (AHP) accompanied by fuzzy sets theory to determine the most critical component types of distribution power systems to be prioritized in maintenance scheduling is suggested by Dehghanian et al. (2011). In the presence of many qualitative and quantitative attributes, fuzzy sets can effectively help to deal with the existent uncertainty and judgment vagueness. A modular approach for a Reliability Centered Asset Management process for an electric network with cost and quality is presented by Schwan et al. (2007). The goal of the application is the combined control of cost-effectiveness and power quality. Application examples of this asset management process for distribution systems present the definition and calculation of both component importance and component condition indices, as well as a detailed simulation of both supply reliability and economic parameters into the future. Al-Douri et al. (2020) introduced a systematic methodology that accounts for failure early enough during the conceptual design stages. Once a base-case design is developed, the methodology starts by identifying the sources of failure that are caused by reliability issues, including equipment, operational procedures, and human errors for a given process system or subsystem. This helps identification of critical process subsystem(s) that are more failure-prone or cause greater downtime than other subsystems.

Bayesian and Monte Carlo techniques are utilized to determine the appropriate distributions for the failure and repair scenario(s), respectively. Markov analysis is used to determine the system availability. The economic potential of alternative design scenarios is evaluated with the objective of maximizing Incremental Return on Investment (IROI) is utilized to make a design decision. Ferreira et al. (2015) presented the key considerations on the reliability and operation of high-efficiency motors, offering a comprehensive perspective on the advantages, drawbacks and limitations of high-efficiency industrial motors. A comparison of the life expectancy of IE2-, IE3- and IE4-Class motors under unbalanced and distorted voltage supply is considered. It also demonstrated how moving to a higher efficiency class can avoid investing in a larger motor. Hacke et al. (2018) describe the projects and relevant background needed in developing design qualification standards that would serve to establish a minimum level of reliability, along with a review of photovoltaic inverter quality and safety standards, most of which are in their infancy. In this paper, authors have compared stresses and levels for accelerated testing of inverters proposed in the standard drafts and those proposed by manufacturers and purchasers of inverters. Design validation testing using realistic operation, environmental, and connection conditions, including under end-use field conditions with feedback for continuous improvement, is recommended for inclusion within a quality standard.

## 3. RELIABILITY ASSESSMENT AND ANALYSIS MODEL (RAAM)

A structured Reliability Assessment and Analysis Model is highly desired to handle such assessment to address this problem properly. We have introduced a reliability analysis model shown in Figure 2. This model can be used for different systems in asset-intensive industries to perform reliability assessments.
The objective of the assessment is to utilize the existing model to structurally apply to address reliability. This assessment is to analyze the common failures experienced by the subject motors and utilize the data to reduce the average maintenance downtime of the propane compressor motors by enhancing the motor coupling maintenance strategy, such as the rubber blocks replacement and upgrade coupling type. Out of the population of motors in operation, a set of eight motors are identified which have experienced failures during the last five years. The Pareto analysis was carried out on this set of motors to further narrow down the group of motor failure modes with the worst performance. The primary target for further investigation and Weibull reliability analysis is this group of motors.

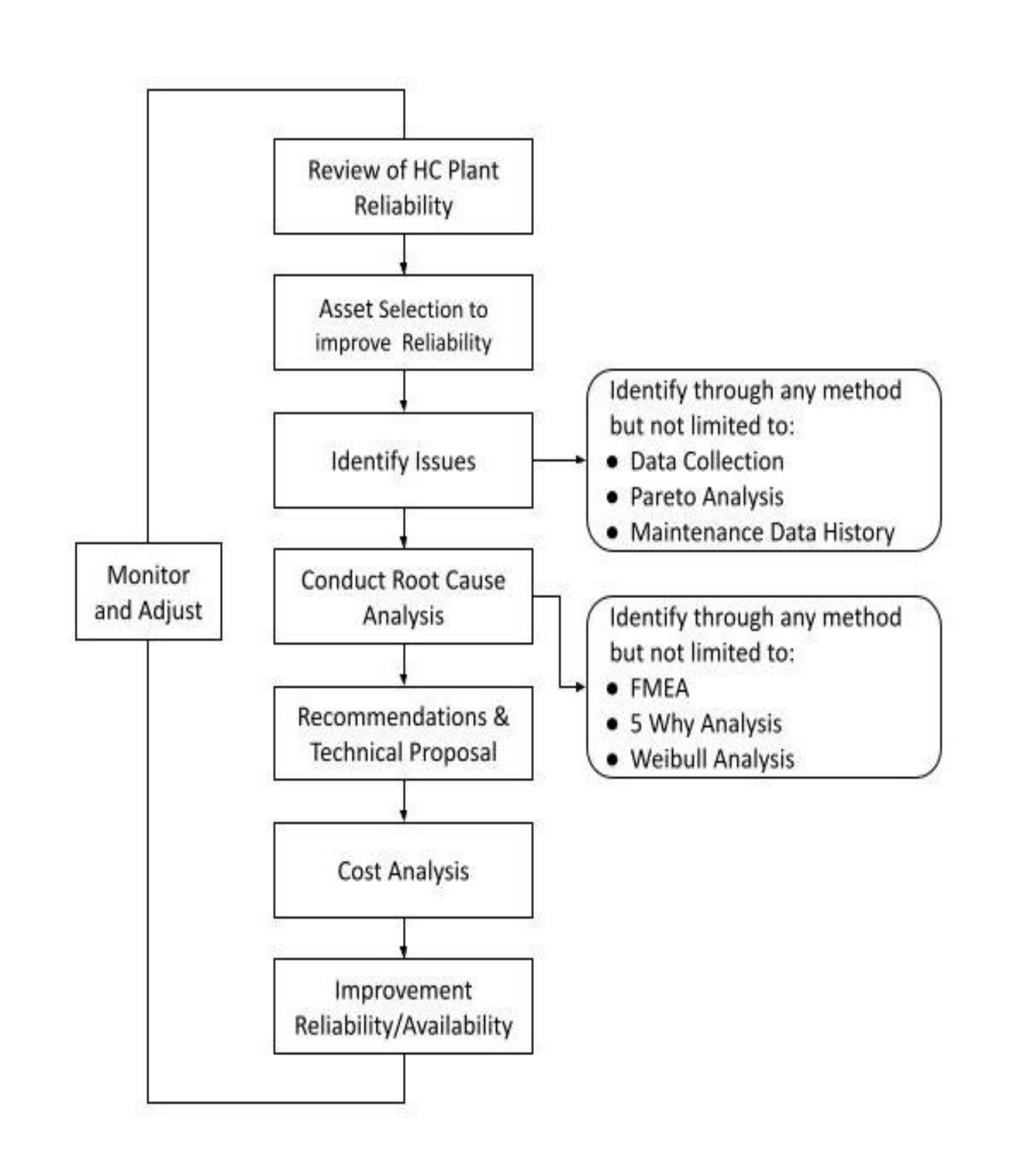


**Figure 2.** Reliability Assessment & Analysis Model.

**Table 1**. Basic Data – Synchronous Motors.

| Specification. | Value |
|---|---|
| Horsepower | 21,000 hp |
| Power | 3450 kW |
| Voltage | 13,800 V |
| Current | 184 A |
| Frequency | 60 Hz |

**Table 2**. Average Motor Operating and Downtime Data.

| HP Motors | Average Time (Hours) | Downtime (Hours) | MTBF | MTTR |
|---|---|---|---|---|
| M-A | 33695.50 | 1368.50 | 8423.88 | 342.13 |
| M-B | 34438.20 | 625.80 | 8609.55 | 156.45 |
| M-C | 33580.90 | 1483.10 | 8395.23 | 370.78 |
| M-D | 34800.16 | 263.84 | 8700.04 | 65.96 |
| M-E | 33639.40 | 1424.60 | 8409.85 | 356.15 |
| M-F | 34121.90 | 942.10 | 8530.48 | 235.53 |
| M-G | 34600.07 | 463.93 | 8650.02 | 115.98 |
| M-H | 33657.90 | 1406.10 | 8414.48 | 351.53 |

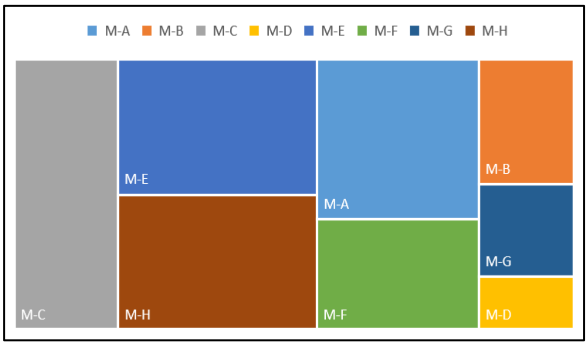


**Figure 3**. Treemap – Mean Time to Repair of Motors.

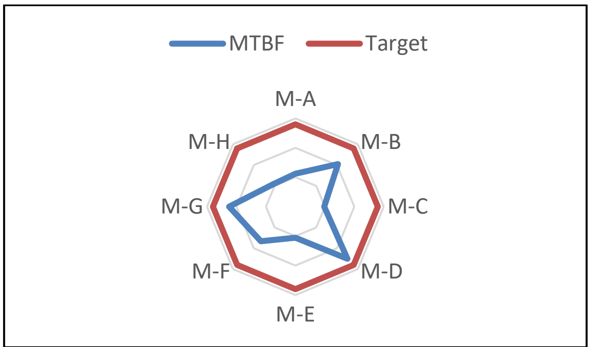


**Figure 4.** Difference between Existing and Target MTBF.

The analysis started by determining each electric motor failure mode. The highest number of failures are attributed to the failure of motor couplings followed by downtime due to overhaul, rotor, bearing, etc. Coupling rubber blocks are essentially non-repairable products and are being replaced upon failure now. Most motor failures are found to be due to the coupling of rubber blocks. Some of the basic data for the motors are provided in Table 1.

The motor failure data has been gathered, and the results have shown that for the past four years, the average annual maintenance unavailability for the equipment is around 10.4 days of downtime per year per motor, as shown in Table 2.
Treemap shown in Figure 3 exhibits the average repair time of the motor, whereas, Figure 4 shows the current MTBF vs target MTBF.

### *3.1 Asset Identification*

The first step is to review the overall reliability and maintenance data to identify the bad actors or assets that require attention. Generally, at facilities, there are monthly or weekly data analyses to review and identify such assets with poor reliability. One of the very common techniques to perform such activity is Pareto Analysis. Pareto analysis provides us with an opportunity to identify the few items causing major issues, commonly known as the 80-20 rule. 80% of the problems can be addressed by addressing 20% of the causes. Shweta et al. (2018) and Taman & Tanya (2015).

### *3.2 Pareto Analysis - Identify Issues / Problems*

The Pareto analysis method is used to define a given problem by viewing the common failures experienced on the motor to determine which failure mode is affecting the machines. It is a decision-making analysis method that separates a statistically limited number of input factors into the largest effect on a desired or undesired result. Pareto analysis is based on the idea that 80% of a benefit can be achieved by carrying out 20% of the work. The time of failure, type of failure, and repair cost of each motor is housed in the Maintenance Management System. The data period of our investigation, from January 2004 to January 2007, is limited to four years. Eight motors are those whose four-year history has been reviewed. The common failures experienced by any rotating equipment can be broken down into four major categories: Vibration, Electrical, Instrument, and Manufacturing Error. The data was collected for all eight motors to determine which failure mode is most common and how that failure contributed to the system downtime.

Most of the failures experienced were with 70.9% of high vibration and 26.6% of an electrical fault, as can be witnessed in Figure 5. The high vibration downtime contributed to a total of 2215 hours; vibration issues with the motors contribute 70.9% of the overall failure modes.

A detailed assessment of data vibration failure symptoms, the two most common failures within that realm are coupling and rotor. The coupling failures make up around 73% of the total vibration failures experienced on the eight motors during the analysis, as shown in Figure 6.

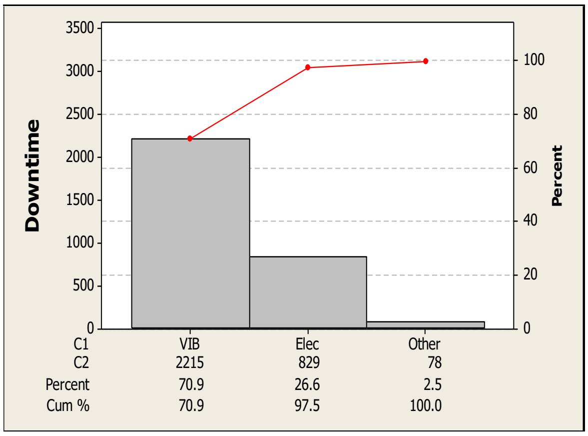


**Figure 5.** Pareto Chart of Motor Failure Modes.

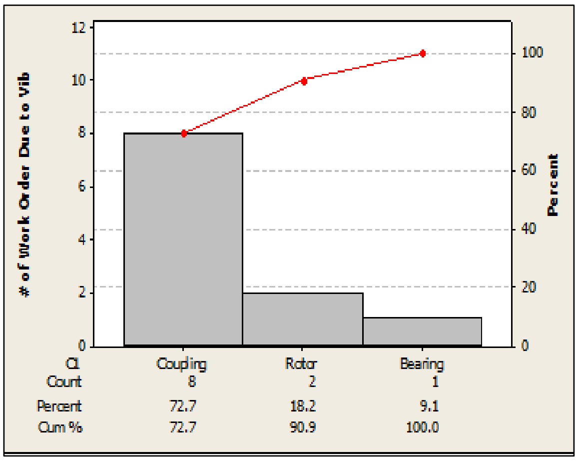


**Figure 6.** Pareto Chart of Vibration Failures.

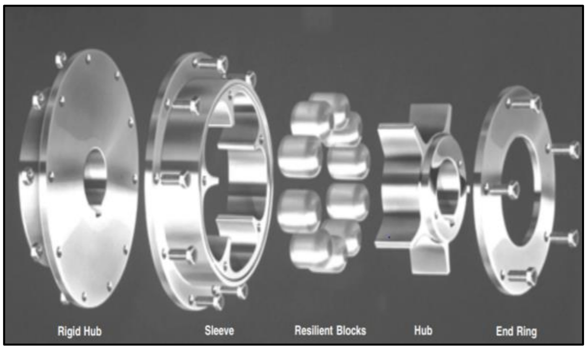


**Figure 7.** Basic Coupling Sub-Components.

**Table 3**. Basic Data – Coupling Failures.

| No of Couplings | Time to Failure (Hours) |
|---|---|
| 1 | 30,000 – 35,000 |
| 2 | 35,000 – 40,000 |
| 5 | 40,000 – 45,000 |
| 3 | 45,000 – 50,000 |
| 6 | 50,000 – 55,000 |
| 8 | 55,000 – 60,000 |
| 7 | 60,000 – 65,000 |

**Table 4**. 5 WHY – Motor failure (Vibration).

| Why | Cause |
|---|---|
| Why did the motor fail? | Vibration |
| Why does vibration occur? | Coupling Misalignment |
| Why does coupling misalignment occur? | Failures of Blocks caused by misalignment (70%) |
| Why did coupling Rubber Blocks fail? | Rubber Blocks service lifetime. |

### *3.3 Root Cause Analysis (RCA)*

Root cause analysis is a structured method of exploring the root cause of failures. There are many processes to conduct root causes, such as 5-Why, FTA and PROACT. Each method has a different way of getting to the root cause, which is not part of the discussion.

An RCA was carried out to understand the causes of the failure of the motor system. Motors are equipped with a non-lubricated flexible coupling designed to transmit torque via rubber blocks, as shown in Figure 7.

As it is used to absorb intense shocks during start-up and any abrupt change in load, rubber blocks are an essential part of the coupling design. Due to the continuous operation of the motors, the material and type of rubber blocks play a major role in their durability. Maintenance data analysis has shown that the coupling rubber blocks for all the motors have been replaced for the first time, as per Table 3, following the failure running hours.

In this assessment, motor failures were analyzed by some of the common Root Cause Analysis (RCA) techniques as follows: 5-Why is a method of questioning used to determine the cause and effects of a particular problem or failure? The first why usually starts with a question such as why did the motor fail? The answer forms the foundation of the next question until you get to something fundamental, as shown in Table 4. The number five is based on the observation that the general problem is typically resolved by asking 'why' four to five times. The five why the technique is also commonly used during a vibration-related failure symptom as a troubleshooting guide to determine the potential root cause.

The impact of coupling misalignment due to defective rubber blocks on vibrations is debated in the field. There are different explanations for why misalignment causes the 2X (2-times speed) vibration frequency problem. Fig. 8 shows the cracked rubber blocks, and they have contributed to the problematic frequency.

**Figure 8**. Failure and Cracks of Rubber Blocks.

**Table 5**. Weibull Analysis – Dataset.

| Time to failure (Hours) | Cumulative per cent f(t) of couplings failed | (t- $t_0$) $t_0$ = 20,000h | (t- $t_0$) $t_0$ = 25,000h | (t- $t_0$) $t_0$ = 30,000h |
|---|---|---|---|---|
| 30,000-35,000 | 1 | 15,000 | 10,000 | 5,000 |
| 35,000-40,000 | 3 | 20,000 | 15,000 | 10,000 |
| 40,000-45,000 | 8 | 25,000 | 20,000 | 15,000 |
| 45,000-50,000 | 11 | 30,000 | 25,000 | 20,000 |
| 50,000-55,000 | 17 | 35,000 | 30,000 | 25,000 |
| 55,000-60,000 | 25 | 40,000 | 35,000 | 30,000 |
| 60,000-65,000 | 32 | 45,000 | 40,000 | 35,000 |

### *3.4 Failure Modes and Effect Analysis*

Analysis of Failure Modes and Effects Analysis (FMEA) is by far the most comprehensive tool available for identifying causes. It is an inductive process that can start at the level of the component (shaft, bearing, coupling, etc.). Referring to the table in Appendix A, the result of the FMEA analysis showed that the motor coupling high vibration failure mode is the highest risk probability among the other failure modes.

### *3.5 Weibull Analysis*

The Weibull reliability analysis is found to be very useful in characterizing the time of the equipment to failure data and designing appropriate maintenance strategies using the Weibull model as a predictive model Black and Geitam (1997), Kelly (1997), Ben-Daya and Dufuaa (2000), and Jeong and El-Sayed, (2000). The two Weibull Cumulative Distribution Function (CDF), F(t) parameters define the fraction failure or the likelihood of failure before time t (or unreliability at time t) and have an explicit equation Lewis (1987), Abernathy et al. (1983), Kapur and Lamberson (1977).

The Weibull cumulative density function for two-parameter is given by Abernethy et al. (1983):

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad 1$$

And the Weibull reliability function for two parameters is:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad 2$$

The shape factor (β) is non-dimensional and reveals the type of failure mode, such as early life failure (β<1), constant life (β=1), or wear-out (β>1) on the bath-tub curve. The other Weibull parameter (η) is a characteristic life having the same unit as t, and is a function of the mean time to failure (MTTF). The general relationship between η and MTTF is given by the following equation: (Lewis, 1987)[15]

$$MTTF = E(T) = \eta\Gamma\left[1 + \frac{1}{\beta}\right] \qquad 3$$

where β is the shape factor, $\eta$ is characteristic life, and $\Gamma$ is the gamma function,

Coupling rubber block failures data have been extracted from the maintenance records with estimated different guaranteed life t0 and are prepared, as shown in Table 5, for plotting on Weibull probability plotting paper.

The straightest plot is produced, as shown in Appendix B (Figure 9); the guaranteed lifetime zero (t0) is taken to be 30,000 hours and gives the probability that 63% of the couplings fail at characteristic life (η) of about 51,000 hours, or 5.8 years and a β-value of about 2.2 (indicating a wear-out phase of failure).

The gamma function value Γ(•) is 0.886; the current MTTF calculation is = η * 0.886 = 51,000 * 0.886 = 45,186 hours, with β greater than one (1) and the MTTF is 5.1 years of service, the scheduled rubber blocks replacement interval can be read directly from the plot at an acceptable or allowable Probability of Failure (PoF). The cumulative failure probabilities at 35,000 hours are 30% which is the suitable time to schedule rubber blocks replacement of the service life. Also, the reliability will be improved to 70% at a lifetime of 35,000 hrs.

### *3.6 Reliability Analysis Summary*

The major findings of reliability analysis are summarized as follows:

a. The time to failure and downtime data of the high HP motors were collected from the computer maintenance management system, monthly operator's on-site log record in the motor running hours, and from online monitoring of process variable data retrieved from the distributed control system of the gas plant. The period of investigation is based on the data from 2004 to 2007. All of these motors were thoroughly analyzed as their non-repairable parts were analyzed separately, such as coupling.

b. Motors are found to have a high average annual maintenance downtime of around 10.4 days (2.84% unavailability) of downtime per year per motor.
c. To identify the most critical motor failure mode, the Pareto analysis was efficiently used. Two main factors depend on the Pareto analysis criteria, which are the number of failures and downtime. The high-vibration failure mode is the most critical, as shown in the Pareto analysis (around 70.9%).
d. To visualize the relative contribution of each failure mode, the failure modes of motors are figured out and plotted in Pareto charts. The outcome shows that the high vibration of motors has the highest failure mode with a total downtime of (3,122 hours).
e. The high vibration failure mode was analyzed by Pareto analysis to identify the most critical sources of this vibration. Motor couplings were found to be the main source of the high vibration due to misalignment.
f. Motor coupling root cause analysis (RCA) was conducted to identify the root cause of the high vibration. Five why and FMEA techniques were used as reliability tools to find the cause of coupling failure. The defective rubber blocks at the coupling were identified as the main root cause of the coupling misalignment.
g. The various reliability parameters and indices of these most critical motor couplings are $\beta$ and $\eta$. The Weibull reliability analysis is found to be very beneficial to characterize the equipment's main time to failures of the motor couplings and to select an appropriate maintenance strategy for a given coupling.

### *3.7 Cost Analysis Summary*

The main objective of this section is to transform the reliability assessment results into financials to justify improvements or to make the right decision. One of the important portions of any reliability analysis is cost analysis. The equipment failure rates and the consequences of engineering practices on life equipment should be defined. To communicate clearly technical outcomes within the organization, it is always proven beneficial to convert the results of equipment life and failures into a financial analysis.

Assumptions:

1. One Motor failure will result in the loss of the feed to the gas plant by 230 MMSCFD (million standard cubic feet per day)
2. The natural gas industrial price = is 3.5 USD per thousand cubic feet.

The cost of unreliability is equal to 805 thousand USD/day due to the loss of a machine. The total of 10.4 days of downtime per year costs USD 8.372e6 per year. The reliability assessment and data analysis have demonstrated that the rubber blocks of the motor coupling are the main reason for the high value of the cost of unreliability. For wear-out failure modes, the cost of an unplanned failure is much greater than the cost of a planned replacement; there will be an optimum replacement interval for minimum cost.

## 4. RECOMMENDATIONS

Based on financial and reliability analysis, the following major recommendations were developed to address reliability and maintainability.

1. Develop preventive maintenance tasks to schedule replaces the coupling rubber blocks at a fixed 4-year interval of service life which will reduce the gas plant downtime from 10.4 days/year to 5 days/ year. This technical proposal will improve reliability figures, increase equipment availability and approximately reduce the cost by 52% of unreliability.
2. As an alternative, upgrading the existing coupling type with dry flexible metal coupling can have the following advantages:
   - All Steel Design
   - Maintenance-free and Wear-free
   - Angular, Radial and Axial flexible
   - Torsional Rigid and Free of Play
   - Temperature Stability
   - Easy Installation
   - Smooth Operation

The flexible metal coupling costs a maintenance-free option for at least ten years of service life, which will eliminate machine downtime. Against the maintenance cost, the new coupling is well justified for improving the reliability and overall productivity of the facility.

## 5. CONCLUSIONS

This paper proposed a structured model to address long-term maintenance and reliability issues. This paper provides an application of the proposed model and a detailed analysis based on historical maintenance and reliability data. In the paper, some tools have been discussed and applied to ensure the readers can understand the application part of the data and assessment.

The outcome is very useful for maintenance management and will allow us to take the correct decision in advance based on this analysis to avoid any operational disturbance and plant downtime. Motor failures due to coupling rubber blocks are the highest failure modes, which is 73% of the total number of failures. The reliability analysis shows that an improvement in motor coupling is required to improve the overall cost and gross margins.

The unreliability cost analysis is an effective and practical reliability tool for converting failure information into the cost for facility management to compare the benefits in financial terms. To improve reliability, the cost analysis demonstrated that an investment in motor coupling is well justified.

Finally, the proposed reliability assessment model using this paper certainly paves ways to develop new tools, elements, and methods to improve the assessment. New tools such as smart algorithms, data analytics, big data along with machine learning can certainly improve the outcome of later assessments. These new algorithms and technologies can also help predict the failures earlier to have replacements based on the real condition, which can optimize the maintenance cost. The proposed method can be applied to any application within the oil and gas industry as well beyond in any asset-intensive industries.

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding this article.

## FUNDING

The authors did not receive any funding for this research.

## ACKNOWLEDGMENT

The authors would like to acknowledge Saudi Aramco's management and public relations support.

## REFERENCES

Abernethy, R. B., Breneman, J. E., Medlin, C. H., & Reinman, G. L. (1983). Weibull analysis handbook. Pratt and Whitney West Palm beach fl Government Products Division.

Al-Douri, A., Kazantzi, V., Eljack, F. T., Mannan, M. S., & El-Halwagi, M. M. (2020). Mitigation of operational failures via an economic framework of reliability, availability, and maintainability (RAM) during conceptual design. Journal of Loss Prevention in the Process Industries, 67, 104261.

Bajaj, S., Garg, R., & Sethi, M. (2018). Total quality management: a critical literature review using Pareto analysis. International Journal of Productivity and Performance Management, 67(1), 128-154.

Ben-Daya, M., & Duffuaa, S. O. (2000). Overview of maintenance modeling areas. In Maintenance, Modeling and Optimization (pp. 3-35). Springer, Boston, MA.

Bloch, H. P., & Geitner, F. K. (1997). Practical Machinery Management for Process Plants: Volume 2: Machinery Failure Analysis and Troubleshooting. Elsevier.

Choudhary, A., Goyal, D., Shimi, S. L., & Akula, A. (2019). Condition monitoring and fault diagnosis of induction motors: A review. Archives of Computational Methods in Engineering, 26(4), 1221-1238.

Dehghanian, P., Fotuhi-Firuzabad, M., Bagheri-Shouraki, S., & Kazemi, A. A. R. (2011). Critical component identification in reliability centered asset management of power distribution systems via fuzzy AHP. IEEE Systems Journal, 6(4), 593-602.

Edwin, V. K. D., & Syam, S. A. (2010). Reliability assurance of large electric motors in a process plant. In 2010 2nd International Conference on Reliability, Safety and Hazard-Risk-Based Technologies and Physics-of-Failure Methods (ICRESH) (pp. 642-647). IEEE.

Ferreira, F. J., Baoming, G., & de Almeida, A. T. (2015). Reliability and operation of high-efficiency induction motors. In 2015 IEEE/IAS 51st Industrial & Commercial Power Systems Technical Conference (I&CPS) (pp. 1-13). IEEE.

Hacke, P., Lokanath, S., Williams, P., Vasan, A., Sochor, P., TamizhMani, G., ... & Kurtz, S. (2018). A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols. Renewable and Sustainable Energy Reviews, 82, 1097-1112.

Jeong, H. S., & Elsayed, E. A. (2000). Online surveillance and monitoring. In Maintenance, Modeling and Optimization (pp. 309-343). Springer, Boston, MA.

Kelly, A. (1997). Maintenance strategy. Elsevier.

Kapur, K. C., & Lamberson, L. R. (1977). Reliability in engineering design. New York.

Lewis, E. (1987). Introduction to reliability engineering (No. 04; TA169, L4.).

Liu, X., Li, J., Al-Khalifa, K. N., Hamouda, A. S., Coit, D. W., & Elsayed, E. A. (2013). Condition-based maintenance for continuously monitored degrading systems with multiple failure modes. IIE transactions, 45(4), 422-435

Powell, Taman & Sammut-Bonnici, Tanya. (2015). Pareto Analysis. John Wiley & Sons

Schwan, M., Schilling, K., & De Melo, A. A. (2007). Reliability centered asset management in distribution networks-process and application examples in Electricity Distribution.

Sukhachev, I. S., & Sushkov, V. V. (2016, November). Assessment dynamics of reliability and resource consumption of "Cable—Submersible electric motor" system at West Siberia oil fields. In 2016 Dynamics of Systems, Mechanisms and Machines (Dynamics) (pp. 1-4). IEEE.

Zaiets, N., & Kondratenko, I. (2019). Development of an Intelligent System for Predicting the Reliability of Electric Motors. In 2019 IEEE 39th International Conference on Electronics and Nanotechnology (ELNANO) pp. 614-619.

# APPENDIX A

**Table 6.** Example of Motor FMEA.

| **Process Steps or Product Functions** | **Potential Failure Mode** | **Potential Effects of Failure** | **Severity (1-10)** | **Potential Causes of Failure** | **Occurrence (1-10)** | **Current Controls** | **Detection (1-10)** | **Risk Priority Number (RPN)** |
|---|---|---|---|---|---|---|---|---|
| Motor stator | Short circuit | Motor grounded | 8 | 1. Winding stator service lifetime<br>2. Accumulations of oil and dust on stator winding.<br>3. Damaged stator winding insulation. | 4 | 1. Replace stator insulation with double insulation.<br>2. Partial Cleaning for stator during PM.<br>3. Re-winding motor stator after 25 years of service | | 96 |
| Motor Rotor | High Vibration Rotor coil short | Imbalance rotor | 6 | 1. Accumulations of oil and dust on stator winding.<br>2. Rotor Mass<br>3. Coil service lifetime | 2 | 1. Protection system.<br>2. Rotor balancing.<br>3. Re-winding rotor coil. | 5 | 60 |
| Motor Bearings | High Vibration High temperature | Bearings damage | 6 | 1. Misalignment between motor and gearbox.<br>2. Improper bearing fit.<br>3. Lack of lubrication | 1 | 1. Monitor the vibration level on both bearings in EMP<br>2. Monitor the temperature reading | 6 | 36 |
| Motor Coupling | High Vibration | Misalignment between motor and gearbox. | 7 | 1. Rubber Blocks service lifetime. | 9 | Implement alignment target figures | 5 | 315 |

## APPENDIX B

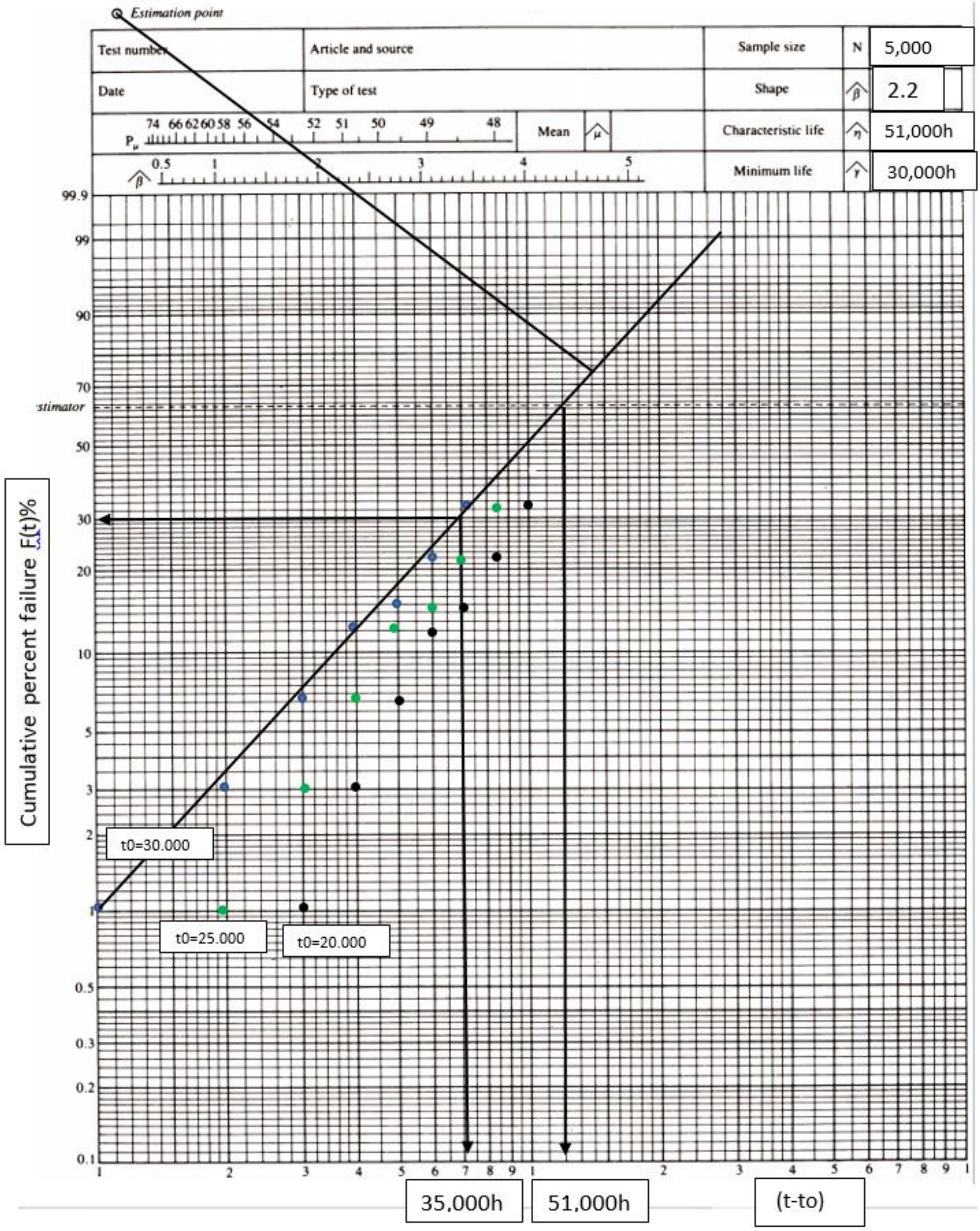


**Figure 9.** Weibull Probability Plot.