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Risk Assessment of Critical Equipment Failure Mode. A Case Study of Olkaria 2 Geothermal Power Plant In Kenya.

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Abstract: *Recently in Kenya, there is massive investment in exploration of geothermal energy which is the key source of power to the national grid. However, despite considerable investment in geothermal power sources, in Kenya and many developing countries, few studies address the asset management (maintenance) aspects of existing facilities. Therefore the objective of this paper is to perform risk assessment of critical equipment failure modes in the power plant by using RPN and FMEA techniques. These techniques were considered for determining, classifying and analyzing common failures in the power plant. The first step involved failure data collection, structuring and analysing the reliability data. The next step involved performing risk assessment with a view of prioritizing critical sub-systems and the critical failure modes associated with the critical sub-systems identified. Risk assessment was done by applying RPN and cost-based FMEA analysis where risk is measured in terms of cost of failure of a sub-system. As a result, an appropriate risk scoring of occurrence, detection and severity of failure modes and computing the Risk Priority Number (RPN) for detecting critical sub system failure is achieved. FMEA technique was then applied to determine the critical failure modes for the critical sub systems identified using RPN. The study found out that the critical sub systems experiencing frequent failures were gear reducer, hot well motors and vacuum pumps. The failure costs associated with these sub systems upon downtime are USD 19,930.67, USD 12,911.27 and USD 8,651.20 respectively.*

Keywords: *Risk assessment, RPN, FMEA, critical sub systems, failure cost.*

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I. Introduction

1.1 Background of the study

Electricity in Kenya is generated from geothermal (47% of consumption), hydropower (39%), thermal (13%) and wind (0.4%). Despite increasing installed capacity, the demand for power in Kenya is rising at a faster rate than the supply, and consumption of electricity per consumer is decreasing. With the huge demand, the government of Kenya is investing heavily in wind, thermal and geothermal energy as reliable sources of energy

With the current changes in climate patterns in Kenya which is attributable to global warming, conventional sources of energy such as hydroelectric and fossil fuel are increasingly viewed as unstainable, thus the conscious effort for alternative sources of energy, and in this instance, renewable energy[1]. In particular, geothermal and wind power are considered attractive given their abundance in Kenya, with a geothermal potential of 10,000 MW and wind power aiming to generate 2,036 MW of wind power, or 9% of the country's total capacity, by the year 2030. In Kenya, geothermal energy can be used to replace a large percentage of fossil fuels for both electricity and thermal energy needs[2].

One of the geothermal power plants in Kenya is the Olkaria 2 power plant with installed electric generating capacity of 105 megawatts (141,000 hp). The power plant is located 125 km North West of Nairobi, and it is owned and managed by KenGen. The plant started its operations in the year 1976 with 2 wells for steam production and it has undergone dynamic growth since then with approximately 270 wells currently and more exploration being done. Each well has an electricity generating capacity of 5MW, with the total generation capacity of the plant currently standing at 105MW[2, 3].

Geothermal energy in Olkaria 2 has mainly been utilized for electrical power production. The plant is expected to ensure maximum output to the national grid at all times, in a requirement that strains the power plant and directly impacts on the maintenance of the power plant. The plant have signed power purchase agreements with very stringent requirements to ensure a high level of output is maintained and to escape the hefty penalty that can be occasioned by failure or downtime[3]. Through KenGen, the plant sells it power to

Kenya Power in wholesale at a cost of approximately US$0.088KWh hence the need for plant reliability and availability so as to minimize any production output loss.

In many cases, any unavailability in the power plant is attributed to equipment failure which affects greatly and negatively the cost of operations and the plant's profitability. With such failures the power plant adopts condition monitoring as part of their maintenance programs. A pilot survey carried out by this researcher into the power plant indicated that, the plant uses a Computerized Maintenance Management System (CMMS) to plan for scheduled maintenance. CMMS can be described as a "black hole" this term is coined by the researcher as a description of system greedy for data input that seldom provide any output in terms of equipment or component failure[4].

This being the major challenge of the system in place, the maintenance team often encounter difficulties analyzing equipment performance trends and their causes of failure as a result of inconsistency in the form of the data captured. Therefore, there was need for failure data collection and structuring so as to identify the equipment failure and their failure modes. This was done by use of both RPN and FMEA methodology.

1.2 Research problem

Geothermal energy is a resource that is gaining wider utilization in Kenya and therefore there is a high pressure for the existing plant (Olkaria 2 power plant) to be reliable and available to satisfy the ever increasing energy demand. Nonetheless an initial interaction with the maintenance department in the power plant highlighted several maintenance related challenges which include an over reliance on Computerized Maintenance Management Systems (CMMS). The CMMS only provides bulky information on incidences or occurrences that might have affected the power/production (MW) output. The system is used to give suggestions on preventive maintenance rather than identification of equipment or system failure that could have contributed to power output loss. Unexpected failures in the power plant usually have adverse effects on the environment, may result in major accidents and affects the output production cost. Therefore in order to minimize the risk of failure in the power plant a structured methodology in maintenance must be put in place. This can be first achieved by adopting a structured risk assessment approach to the study of component/equipment failure modes. This research study on risk assessment of critical equipment failure modes for geothermal power plant intends to provide a structured approach in identification of critical equipment and their respective failure modes.

1.3 Research objective

The aim of this research is to perform risk assessment with a view of prioritizing critical equipment failure modes.

II. Literature Review

2.1 Risk assessment

Risk assessment is a technique for identifying, characterizing, quantifying, and evaluating failure of an equipment or machines[5]. Risk assessment process also utilizes experiences gathered from project personnel including managers, other similar projects and data sources, previous risk assessment models, experiences from other industries and experts, in conjunction with analysis and damage evaluation/prediction tools. A risk assessment process is commonly a part of a risk-based or risk-informed methodology[6].

The risk analysis method aims at the evaluation of the likelihood of occurrence of equipment failures and their consequences for the power plant operation, characterizing a quantitative risk analysis. The output of a quantitative risk assessment will typically be a number, such as cost impact (Kshs) per unit time. The number could be used to prioritize a series of items that have been risk assessed. Risk assessment of the various components in the system paves way for the identification of critical components[6]. Thus focusing on the critical components rather than examining all the components in the system has an advantage of optimum usage of maintenance resources.

2.1.1 Failure Mode and Effects Analysis (FMEA)

FMEA is used to identify possible failure modes, their causes and the effects of these failures[7]. The failure modes of a system depend on the functional arrangement of the components and on the type of the components. Although those failure modes vary greatly due to the functional architecture, the initial failure events, the components failure modes, can be easily classified. The severity, probability of occurrence and risk of non-detection are estimated and used to rate the risk associated with each failure mode[8].

According to[1], Failure Modes and Effects Analysis (FMEA) is a systematic method for analyzing and ranking the risks associated with various products (or processes), failure modes (both existing and potential), prioritizing them for remedial action, acting on the highest ranked items, re-evaluating those items and returning to the prioritization step in a continuous loop until marginal returns are achieved. [9]showed that FMEA technique is a systematic analysis to identify all of the functions or components of the system to determine ways in which a failure can occur, and to define the resulting effects of the failures on the system under consideration.

Application of the FMEA procedure of risk analysis on Geothermal Power Plant was done by[1], where he based his analysis by utilizing the aspect of Risk Priority Number (RPN) in classifying and analyzing common failures in the power plant. The risk priority number (RPN) is not a measure of risk, but of risk priority. By calculating the value of RPN, it will be easy to allocate the limited maintenance resources to the most important failures. [10]derived a formula for the calculation of RPN. He indicated that, RPN is the multiplication of severity of failures (S), their probability of occurrence (O), and the possibility of detection (D).

RPN = S x O x D. Table 1.1, 1.2 and 1.3 shows the rating scales for severity (S), occurrence (O) and detection (D) respectively.

Table 1.1: Severity rating scale for GPP FMEA[11]

Rate of severity	Description
1-2	Failure is of such minor nature that the operator will probably not detect the failure
3-5	Failure will result in slight deterioration of part or system performance
6-7	Failure will result in operator dissatisfaction and/or deterioration of part or system performance
8-9	Failure will result in high degree of operator dissatisfaction and cause non-functionality of system
10	Failure will result in major operator dissatisfaction or major damage

According to the formula, severity refers to the immensity of the last effect of a system failure. From Table 1.1, a rate of 10 is allocated to the failure will result in major damage. Occurrence refers to the probability of a failure to occur, which is described in a qualitative way and this is shown in Table 1.2. Detection refers to the likelihood of detecting a failure before it can occur and this is shown in Table 1.3.

Table 1.2: Occurrence rating scale table[11]

Rank of occurrence	Description
1	An unlikely probability of occurrence: probability of occurrence < 0.001
2-3	A remote probability of occurrence: 0.001 < probability of occurrence < 0.01
4-6	An occasional probability of occurrence: 0.01 < probability of occurrence < 0.10
7-9	An occasional probability of occurrence: 0.10 < probability of occurrence < 0.20
10	A high probability of occurrence: 0.20 < probability of occurrence

Table1.3: Detection rating scale for GPP FMEA[11]

Rank of detection	Description
1-2	Very high probability that the defect will be detected
3-4	High probability that the defect will be detected
5-7	Moderate probability that the defect will be detected
8-9	Low probability that the defect will be detected
10	Very low (or zero) probability that the defect will be Detected

The severity, occurrence and detection factors are typically ranging from 1 to 10. The various failure modes are then prioritized based on their criticality as per the RPN value. For instance, a failure mode with an occurrence of 10, severity of 10 and detectability of 10 will have an RPN of 1000, hence will be assigned the highest criticality, necessitating prompt maintenance intervention.

III. Materials And Method

3.1 Research design

A case study approach was adopted as the main research design which entailed an in-depth investigation of the plant failures with a view of developing enhanced maintenance strategies so as to mitigate equipment failure.

3.2 Failure data collection and structuring

In this study, raw maintenance data detailing failures recorded from the power plant was used in the analysis. The data was recorded in free-text style form and collected over a two year period (2014-2016). The data obtained was linked to different systems of the power plant which were identified based on equipment that experienced frequent failures from the plant maintenance records and reports. The data on the sub-systems identified included: Cooling fans, Gear reducer, motors, Hotwell pump, Hotwell pump motor, pumps condenser, nozzles and Two phase pipeline. A sample of the raw data from the maintenance record books from the power plant is as shown in Table 1.4

Table 1. 4: Sample of raw data from the power plant maintenance records

Equipment failed	Occurrence that affect MW output	Stop Date	Start Date	Stop Time(hrs)	Start Time(hrs)	Loss hours	Loss MWh
Gear reducer	High Vibrations	01/10/2014	02/10/2014	1345	0610	16.42	72
	Worn out bearings	10/12/2014	10/12/2014	1032	1600	5	24
Cooling fans	Damaged fan blade	10.03.2014	10.03.2014	1510	1200	21	92
Hot well motors	Bearing failure	07.05.2014	07.05.2014	1235	1525	3	10
Vacuum pumps	Oil leaks	12.08.2015	12.08.2015	1040	1340	4	4

From the failure data obtained, there was need to appropriately structure and organize the data as per the objective of this research study. Structuring was necessary for extracting important and relevant information such as the cost of spares used, man-hour cost, and output production loss among others. The data was then arranged so as to capture these key parameters which would then form a basis of calculating RPN and performing the cost based FMEA. The structured failure data for gear reducer sub system is shown in Table 1.5.

Table 1.5: Structured field data for the power plant for gear reducer sub system**.**

Sub system failed	Failure mode	Effect	Remedy	Failure date and time	Return date and time	Unavailable Time (hours)	Repair time (TTR)	Unavailable MWH (UM)	Value of spares used(USD)(S)	No. of technicians (T	Man-hour unit cost (USD) (CM)	Outage Production Loss (USD) (CP)	Total Cost (USD) (TC)
Gear reducer	Vibrations high	Misalignment	Quality spares and routine maintenance	10/1/2014 11:45	10/1/2014 16:10	4.42	4.42	19.43	517.00	1	88.33	1710.13	2315.47
	Vibrations high	Misalignment	Routine maintenance	12/9/2014 10:00	12/9/2014 15:00	5.00	5.00	22.00	405.00	2	200.00	1936.00	2541.00
	Knocking sound		Check fan shroud clearance	4/15/2014 10:30	4/15/2014 16:50	6.33	6.33	27.87	303.00	1	126.67	2452.27	2881.93
	Knocking sound		Correct the clearance of the fan shroud and the blade	6/23/2015 9:46	6/23/2015 15:30	5.73	5.73	25.23	50.00	1	114.67	2219.95	2384.61
	Vibrations high	Misalignment	Routine maintenance	9/20/2015 9:50	9/20/2015 12:00	2.17	2.17	9.53	120.00	1	43.33	838.93	1002.27
	The drive motor drawing a lot of current		Correct the blade angle	4/2/2015 8:40	4/2/2015 18:00	9.33	9.33	41.07	315.00	1	186.67	3613.87	4115.53
	Damaged fan blade		Replace	11/9/2014 12:50	11/10/2014 17:20	28.50	28.50	125.40	934.00	2	1140.00	11035.20	13109.20
	Damaged fan blade		Replace	8/12/2015 8:15	8/12/2015 14:00	5.75	5.75	25.30	979.00	2	230.00	2226.40	3435.40
	Micro pitting of bearings		Lubrication of bearings	5/15/2014 12:30	5/15/2014 14:50	2.33	2.33	10.27	69.00	2	93.33	903.47	1065.80
	Damaged fan blade		Replace	5/1/2015 10:10	5/1/2015 16:20	6.17	6.17	27.13	875.00	1	123.33	2387.73	3386.07

3.3 Risk assessment

3.3.1 Risk identification

Prior to identifying failure risks of the geothermal power plant, the plant was decomposed into the sub-system identified from the maintenance records and the interview sessions. The information obtained was then structured such that the cost-based FMEA approach could be used for prioritization using RPN. The RPN table is shown in Table 1.6 and it includes information on the type of sub-system the failure originated from, the failure modes, the occurrence rate, severity rate, detection rate. From the occurrence, severity and detection rate, the RPN value was then computed. The RPN value was primarily applied for prioritizing the critical sub-systems, after which, a more detailed prioritization of the failure modes embedded in each sub-system was performed. The prioritization of the failure modes in each of the sub-system was performed using the cost-based FMEA, where cost related data was applied as the prioritization metric.

3.3.2 Risk prioritization

3.3.2.1 Sub-system prioritization

For the sub-systems, the prioritization was done by first computing the RPN for each of the different sub systems identified in the power plant, which includes; Cooling fans, Gear reducer, motors, Hotwell pump, Hotwell pump motor, pumps condenser, nozzles and Two phase pipeline. The critical sub-system were ones having high RPN value relative to other sub-systems. Table 1.6 shows the computation of RPN for the gear reducer sub-system where RPN is computed by multiplying of the severity of failures (S), their frequency of occurrence (O), and the possibility of detection (D), as indicated by the equation below:

Risk Priority Number = Severity X Occurrence X Detection Where: Severity refers to the immensity of the last effect of a system failure Occurrence refers to the probability of a failure to occur. Detection refers to the likelihood of detecting a failure before it can occur

Table1.6: Failure data for determining RPN value for gear reducer.

Sub system failed	Failure mode	Frequency	Occurrence (O)	Severity(S)				Detection(D)	RPN
				Spare parts	Technicians	Down time	TOTAL		
Gear reducer	Vibrations high	3	**8**	3	1	2	**6**	3	144
	Knocking sound	2	**2**	1	1	1	**3**	3	18
	Motor drive drawing a lot of current	2	**4**	1	1	1	**3**	6	72
	Damaged fan blade	3	**3**	4	1	4	**9**	4	108
	Micro pitting of bearings	1	**2**	3	1	2	**6**	3	36
TOTAL			**19**				**27**	**19**	974.7

As an example, the RPN computation for the failure mode 'Vibrations high' is calculated as:
RPN = 8 (Occurrence) × 6 (Severity) ×3 (Frequency) = 144
It should be noted that the severity is calculated as a product of spare parts used or required, need for a technician (where a high value indicates urgent need for a technician to perform the repair), and downtime (where a low value, e.g. 2 for the example indicates limited downtime associated with the failure mode 'Vibrations high). Overall, the RPN value for the 'Gear reducer' sub-system is mathematically expressed as:
Overall RPN for sub-system = $\sum (O) \times \sum (S) \times \sum (D)$.
Hence, from Table 1.6, the overall RPN for gear reducer is 974.7.
The same procedure was followed for computing the RPN for the other sub-systems was done using the same format as for the gear reducer discussed.

Table 1.7 shows the overall values of RPN for the other identified sub-systems.

Table 1.7: Summary of RPN values for the sub system

Sub system	RPN
Gear reducer	974.7
Hot well motors	881.6
Vacuum pumps	627
Two-phase pipeline	326.4
Hot well pumps	280.5
Motors	216
Re-injection condenser pumps	98
Flow control valve	63
Cooling fans	42
Nozzles	4

3.3.2.2 Failure mode prioritization

Failure mode prioritization was done using the Cost-based FMEA approach where costs associated with each failure mode was computed so as to determine their respective criticality. The costs related to the failure modes were illustrated earlier in Table 1.5 for the Gear reducer sub-system. From Table 1.5, the summation of the failure costs considered the costs such as man-hour cost for the repair action, cost of spares used (if any) and the cost incurred during downtime (outage production). For the gear reducer illustrated in this methodology section, the cost components are computed as follows:

1. The man-hour cost was calculated as a product of time to repair and the number of technicians involved in the repair action. This is expressed as:

CM = LR X TTR X T…………………… (1)

Where: CM – Man our cost.
LR – Industry standard labor rate
TTR – Time to repair

For example, from Table 3.2, the man-hour cost (CM) for one of the 'vibration high' failure modes was calculated as:

CM = 20 × 4.42(Repair time) ×1(No. of technicians) = USD 88.4(Man hour cost)

2. The cost of spares (CS) was obtained from records from the maintenance department. For instance, for the failure mode vibrations high, the spare parts costs was recorded as: USD 517.
3. The outage production loss was calculated as a product of the time to repair and the cost of feed-in-tariffs, and expressed as:

CP = UM + ES…………………………. (2)

Where: UM – Unavailable production

ES – Energy cost.

For example, from Table 3.2, the CP for the 'vibration high' failure mode was calculated as:

CP = 0.0088(Feed in Tariff USD/KWh) ×19.43 (Unavailable MWh) ×1000(KW) = USD 1710.13 (outage production loss)

4. The total failure cost is the summation of all these costs and expressed as:

TC = CP + CM + CS………………………………………. (3)

Where: TC - Total failure cost for a specific failure mode

CP – Outage production cost

CM – Man hour cost

CS – Material or spare parts cost.

For example, from Table 3.2, TC for high vibration failure mode was calculated as:

TC = 88.33(Man-hour cost, CM) + 517(value of spares used, CS) + 1710.13(Outage production loss, CP) = USD2315.47 (Total cost, TC)

After calculating the failure cost for each of the failure modes for the illustrative example of the gear reducer sub-system, using equations 1, 2 and 3, the sum of failure costs (cumulative failure cost) was derived. For instance, the cumulative total failure cost for the 'vibrations high' failure mode was 5858.74 USD (see Table 3.5). This cost was calculated as:

Failure cost (vibrations high) =2315.47 (total cost) +2541.00 (total cost) +1002.27(total cost) = USD 5858.74 (Cumulative total failure cost)

Table 1.8 summarizes the cumulative total failure cost for the different failure modes for gear reducer.

Table 1.8: Failure costs for different failure modes for gear reducer sub system

Gear reducer				
Failure mode	Failure cost (USD)	Percentage	%Cumulative	Frequency of failure
Damaged fan blade	19930.67	52.48	52.48	3.00
Vibrations high	5858.74	15.43	67.91	3.00
Motor drawing more current	5854.33	15.42	83.33	2.00
Knocking sound	5266.54	13.87	97.19	2.00
Micro pitting of bearings	1065.80	2.81	100.00	1.00
Total	37976.08	100.00		

From the results shown in Table 1.8, histogram and Pareto charts were derived where the critical failure modes for each of the critical sub-systems were determined.

IV. Results And Findings

4.1 Sub system prioritization

Upon computation of RPN for the different sub systems identified, histogram and Pareto analysis was performed on the sub-systems, which enabled the researcher to identify the critical sub systems in the power plant. The computed RPN values of different sub system is indicated in Figure 1.1 and were used to determine the critical sub systems. The analysis is based on the results indicated in Table 1.7 indicated in Section 3.5.1.

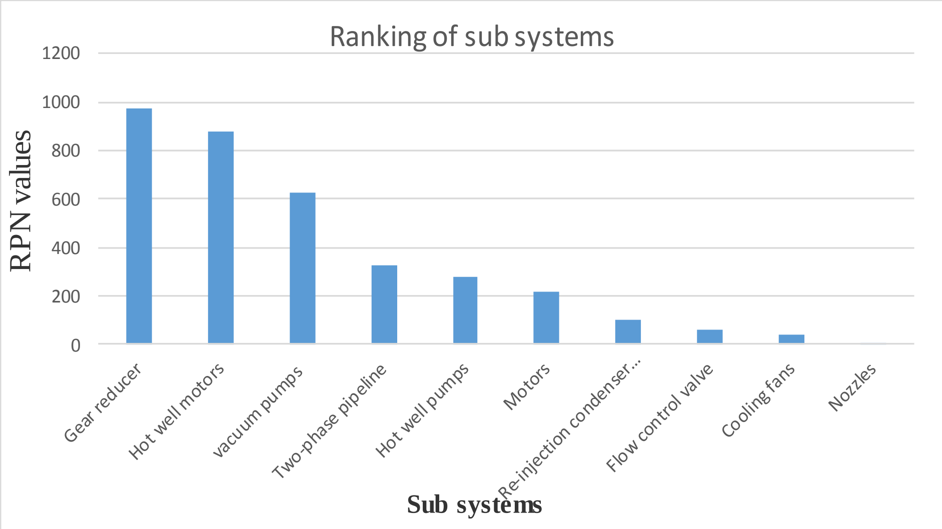

Figure 1.1: RPN ranking of sub system.

From Figure 1.1, the most critical subsystem is gear reducer, followed by the hot well motors and vacuum pumps with RPN values of 974.7, 881.6 and 627.0 respectively. Similarly, the lowest RPNs values were assigned to the flow control valve, cooling fans, and nozzles with RPNs of 63.0, 42.0 and 4.0 respectively. Therefore from the analysis, the gear reducer, hot well motors and vacuum pump are considered the critical sub systems for the power plant based on the high RPN numbers as compared to the rest of the subsystems. These sub systems are further analysed so as to establish their individual failure modes as discussed in section 4.1.1.

4.1.1 Failure mode prioritization

In this section all the failure modes related to each of the critical sub system identified in the in Section 4.1 were analyzed so as to determine the critical failure modes for these sub- system. The cost-based FMEA was used to prioritize the failure modes. Upon computation of the failure costs for each failure modes of the sub-systems, Pareto analysis was carried out for each sub-system on the basis of the total failure cost for each failure mode, from which, the critical failure mode were ranked. The results are discussed as follows.

4.1.2 Failure mode analysis of the gear reducer

In order to determine the critical failure mode of the gear reducer, the cost related to each failure mode was calculated. Pareto chart was used to identify the critical failure mode for the sub system. The values of the calculated failure cost of the failure modes for gear reducer is as shown in Table 1.9 and the Pareto analysis is shown in Figure 1.2

Table 1.9: Cost based FMEA for gear reducer (in USD)

Gear reducer				
Failure mode	Failure cost	Percentage	%Cumulative	Frequency of failure
Damaged fan blade	19930.67	52.48	52.48	3.00
Vibrations high	5858.74	15.43	67.91	3.00
Motor drawing more current	5854.33	15.42	83.33	2.00
Knocking sound	5266.54	13.87	97.19	2.00
Micro pitting of bearings	1065.80	2.81	100.00	1.00
Total	37976.08	100.00		

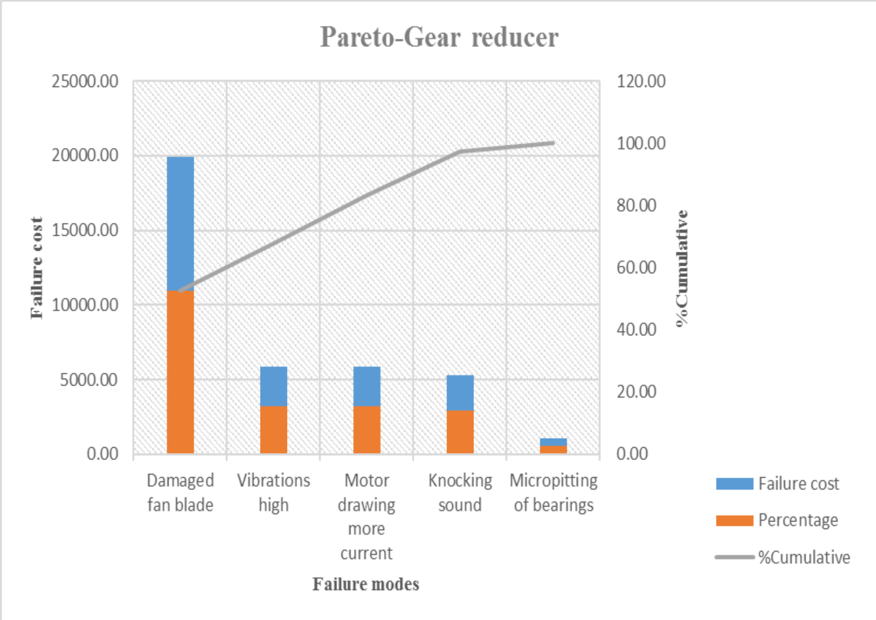

Figure 1. 1: Pareto analysis for gear reducer.

From Figure 1.2, the y-axis represents the total failure cost, percentage of failure and the percentage cumulative while the x-axis represents the various failure modes in the sub system. From the calculation in Table 4.1 and Pareto analysis, the damaged fan blade comes out as the failure mode that represents about 90% of the total failure cost of the gear reducer sub system. The failure cost related to the damaged fan blade is USD 19930 followed by high vibrations with a cost of USD 5858.74. Micro pitting of bearing contributed the least failure mode with a cost of USD 1065.80.

4.1.3 Failure mode analysis of hot well motors

Critical failure mode for the hot well motors was determined by calculating the failure cost related to the failure modes identified. Table 1.10 shows the calculated values of failure cost of failure modes for hot well motors and Pareto chart was used to identify the critical failure mode in the subsystem. Figure 4.3 shows the Pareto analysis.

Table1.10: Cost- based FMEA for hot well motors

Hotwell motors				
Failure mode	Failure cost	Percentage	%Cumulative	Frequency of failure
Bearing failure	12911.27	38.13	38.13	3.00
The motor does not start up	9272.00	27.38	65.51	1.00
Abnormal noise and vibration	8938.80	26.40	91.91	3.00
Antifriction bearing failure	1930.67	5.70	97.61	1.00
Excessive temperature rise	808.67	2.39	100.00	1.00
Total	33861.41	100.00		

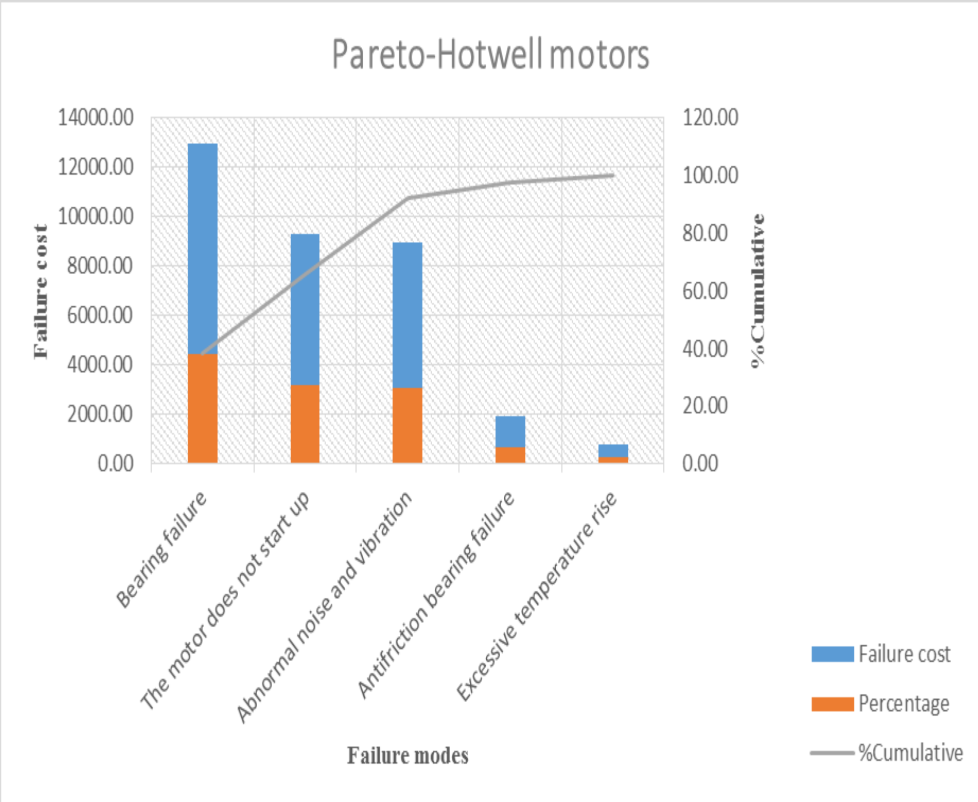

Figure 1.3: Pareto analysis of hot well motors

From the Pareto analysis of the failure modes, failure of bearing, motor not starting and abnormal noise are the most critical failure modes, with the costs of USD 12911.27,USD 9272 and USD 8938.80 respectively. Excessive temperature rise in the motors was the lowest failure mode of the system at a cost of USD 808.

4.1.5 Failure mode analysis of vacuum pump.

In order to determine the critical failure mode of vacuum pump, the cost related to each failure mode was also calculated and Pareto chart was used to show the critical failure mode in the sub system. The calculation is as shown in Table 1.11 and the Pareto analysis is shown in Figure 1.4.

Table 1.11: Cost based FMEA for vacuum pump

Vacuum Pumps				
Failure mode	Failure cost	Percentage	%Cumulative	Frequency of failure
Oil leak on the pump	6880.60	37.71	37.71	3.00
Overheating of bearings	5870.80	32.17	69.88	3.00
High noise level	4073.52	22.32	92.21	1.00
Intense bearing vibration	1421.60	7.79	100.00	1.00
Total	18246.52	100.00		

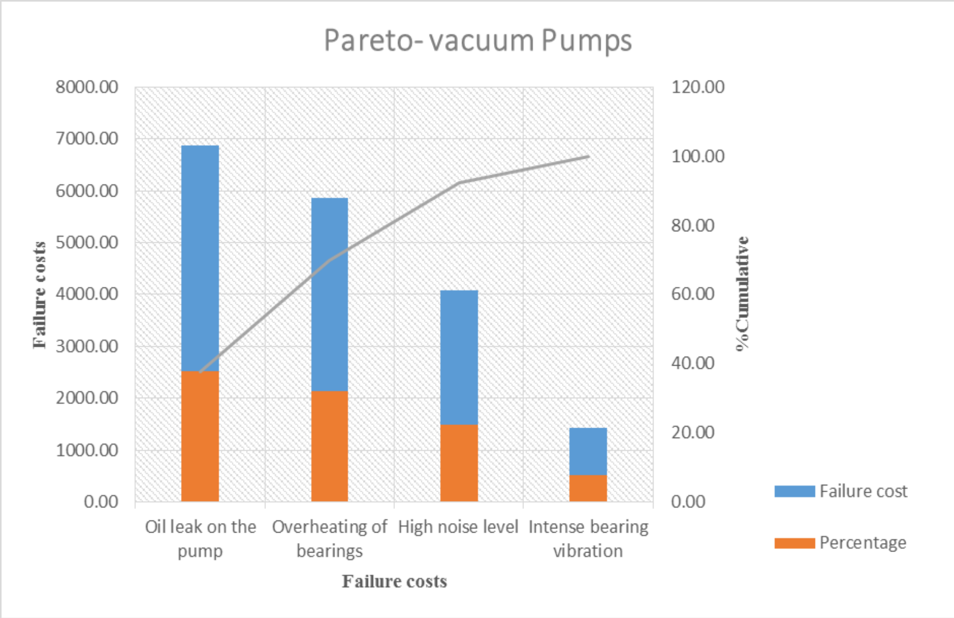

Figure 1.4: Pareto analysis of vacuum pump.

From the Pareto analysis, oil leak on the pump and overheating of bearings had the highest failure costs of USD 6880.60 and USD 5870.80 respectively. The percentage failure cost of the respective failure mode was also high, that is 37% and 32 % and therefore these were the critical failure modes of the sub system. The lowest failure mode was due to intense bearing vibration with a failure cost of USD 1421 and percentage failure cost of 7.79%.

4.2 Summary

This section has outlined the steps involved in risk identification which starts with RPN calculation to determine critical sub system. Cost based FMEA is then applied to further establish the critical failure modes for the critical sub system identified from RPN calculation.

Table 1.12 gives a summary of the results of RPN and cost based FMEA respectively.

Table 1.12: Summary of RPN and cost based FMEA

Critical sub systems	RPN value	Failure mode with highest total failure cost	Failure mode cost ($USD)
1. Gear reducer	974.7	Damaged fan blade	19930.67
2. Hot well motors	881.6	Bearing failure	12911.27
3. Vacuum pumps	627	Oil leak	8651.20

V. Conclusion

The critical sub systems identified were Gear reducer, hot well motors and Vacuum pump. After identifying the critical sub system, failure modes for each of them was then identified. For the gear reducer the critical failure modes identified was damaged fan blade. For the hot well motors, bearing failure was the critical failure mode identified. For the vacuum pump, leaking of oil was the critical failure mode identified. This was achieved by use of RPN and cost based FMEA the techniques helped in determining high potential failure modes.

It is increasingly realized that achieving high-quality maintenance requires prevention of failure at the sources and a focus on identifying and eliminating the risk of critical failures and the causes of equipment deterioration. Utilizing risk based approach by use of cost based FMEA coupled with RPN is observed as very useful in eliminating the chances of equipment failure. Identifying potential failures and the failure modes quickly and taking appropriate actions and making it easier for people to do the right thing are critical to the success of this system

VI. Recommendations

Based on the findings, this study recommends;

1. In order to achieve appropriate and cost effective maintenance there is need for structured format of failure data collection. Data is the foundation to gain control and without effective data gathering, incidents cannot be truly investigated, root causes cannot be solved, improvements is hard to perform and appropriate maintenance policy is difficult to establish. The methodology highlights important data points that need to be included in the design of the CMMS system in place which will then guide the maintenance team on selecting appropriate maintenance policy.
2. By implementing the cost based FMEA and RPN approach, power plant availability can be improved. In order to decide on improvement actions, potential risks and costs arising from various failure modes should be included in the evaluation of potential failure.

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