Proceedings World Geothermal Congress 2020
Reykjavik, Iceland, April 26 – May 2, 2020

Risk-based Maintenance Decision Support for Geothermal Drilling Rigs. A Case Study for KenGen Drilling Rigs

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Keywords: Rig, failure, cost based FMEA

ABSTRACT

Kenya Electricity Generating Company Ltd (KenGen) is the leading power generator in Kenya, producing 69% of the electricity from hydro, geothermal, thermal and wind sources. Geothermal is an abundant resource in the Kenyan rift with KenGen Olkaria field being the largest commercial geothermal project in Africa. However, the lack of adequate and affordable energy in Kenya remains a significant constraint to economic growth, thus, the government of Kenya seeks to accelerate geothermal energy exploration. Drilling accounts for the highest portion of geothermal energy exploration costs. Random equipment failures, high rate of wear and tear, and outright design failures on drilling rig equipment are critical contributors in rendering geothermal drilling a costly exercise. To address these challenges, maintenance is vital to ensure equipment operability, reduced failures and ultimately low maintenance costs. Due to the numerous equipment in an installation, the identification of the critical equipment and subsequent selection of the appropriate maintenance policy to be employed to mitigate its failures is paramount. In this paper, we propose risk assessment techniques that can be applied to structure equipment failure, assess and prioritize failure impact using Pareto analysis to firstly identify critical subsystem and critical equipment under the subsystem, secondly, undertake root cause analysis for the failures on critical equipment and eventually select the most feasible maintenance policies to address the root causes.

The developed methodology is validated using data collected from two Olkaria drilling rigs, where the results show that the top drive and drawworks are the most critical rig subsystems. Furthermore, robotics and electrical controls are the critical equipment under top drive subsystem, while the clutch and brake under drawworks subsystem. The leading causes of rig equipment failure were machine-related wear and tear, overheating and hitting by moving members. Other causes were wrong designs, bad workmanship and poorly translated of manuals. The recommended maintenance actions for the policy framework were Time-based maintenance (TBM), Condition-based maintenance (CBM) and Design out maintenance (DOM) complemented with close supervision of personnel, retraining of staff, the proper translation of manuals and framework contracting for the supply of spare parts.

1. INTRODUCTION

Lack of adequate and affordable energy is a significant constraint to economic growth in Kenya with power outages estimated to cost the Kenyan economy up to 1.5% of GDP growth. Due to averagely high generation costs, Kenya's electricity tariffs are higher compared to neighboring countries such as Ethiopia and Tanzania. As per the installed electric capacity in the year 2013, Kenya electricity generation mix was dominated by hydropower at 49%, fossil fuel at 33% while geothermal, wind and co-generation made up the remaining portion of the total annual installed capacity. However, this has been changing significantly with the Kenya vision 2030 envisaging an additional 5000 MWe into the grid, with geothermal, wind, gas turbine and coal as the cornerstones for this new generation mix (Kant, Masiga, & Veenstra, 2014). KenGen is currently the leading power generator in Kenya with an installed electric capacity of 1633 MWe which is 69% of the country's total installed electricity. Geothermal constitutes 33% of this capacity.

Geothermal is a naturally occurring, clean and abundant resource in Kenyan rift with an estimated electric generation potential of more than 7000 MWe. It has a little environmental footprint, non-climate reliant unlike hydro and is more economical compared to thermal and solar energies. Its exploration starts with a surface reconnaissance to define the resource in terms of the existence of a heat source, presence of hydrological system and the areal extent of the prospect; then drilling is undertaken to provide proof of exploitable steam (Bommer, 2008; Ngugi, 2007). However, rig equipment failure is a contributing factor to the reason why drilling is the most expensive phase of geothermal energy exploration and production. Importantly, by implementing robust maintenance strategies, the organisation is in a better position of minimising the operation and maintenance costs that contribute to the high cost of drilling (Wakiru, Pintelon, Muchiri, & Chemweno, 2019a). This is because, unintended failure of the critical component may require potent significant operation and maintenance cost impacts, for instance, production loss, need for spare parts, loss of plant efficiency. Risk assessment techniques, therefore, can be used to structure potential equipment failures, assess the likelihood of failure occurrence and evaluate failure impact (Simmons et al., 2017).

2. RESEARCH MOTIVATION

Equipment failure is a leading cause of non-productivity on Olkaria drilling rigs leading to downtime and cost overruns. The rig is made up of several types of equipment which have unique failure frequency and severity hence the importance of establishing the critical equipment to derive mitigation measures, in this case, prescribe maintenance strategies. Risk-based maintenance methods rank the failure impact of each rig equipment and assist in recommending a combination of maintenance actions to prevent occurrence as well as minimize the impact of failure. Risk-based maintenance methods that also incorporate the cost impact of the failures are therefore well suited for application on the Olkaria drilling rigs to assist in deriving decision support for the various subsystems and equipment. The objective of the study was to develop a maintenance decision framework that includes the employment of risk assessment techniques to prioritize critical equipment, undertake root cause analysis of the critical equipment and ultimately select maintenance tasks to address the risks identified from the root cause analysis.

3. LITERATURE REVIEW

Today's maintenance faces modern challenges that include rapid technological growth that leads to technologies becoming obsolete quickly. The need to keep both modern and outdated equipment in service means that industries have a combination of new machines with the latest technology and old machines working on obsolete systems hence face significant challenges while prescribing maintenance policies to the different equipment. Maintenance management, therefore, is the determination of the most feasible maintenance policies and actions applicable to the equipment.

3.1 Maintenance actions and policies

Maintenance policies are prescribed regulations that trigger the need for maintenance action. A good policy should be efficient, cost-effective and must conform to the existing processes and environment to guarantee safety and continuity of processes. Maintenance action is the basic intervention tasks carried out as either corrective or reactive. Corrective maintenance is the repair or replace action following a loss or breakdown. It is only carried out when a failure occurs and is for equipment whose breakdown time and costs are less. However, it may lead to reduced equipment availability, where spare parts are not readily available (Wakiru, Pintelon, Muchiri, & Chemweno, 2019b). Furthermore, real causes of failures may not be known; hence, frequent breakdowns can occur. Reactive action is maintenance planned well in advance to avoid random failure. It predetermines what action is to be taken, when and by whom. Instructions are given in greater detail, specific to each equipment and safety is paramount, while the maintenance action taken aims to diminish the probability of failure.

Failure based maintenance (FBM) is a reactive policy where maintenance action is taken when failure has already happened. It is the cheapest form of maintenance approach and doesn't require planning for spare parts, labor and downtime. However, it is not recommended where failure could be catastrophic. Time-based maintenance (TBM) is routine maintenance performed in pre-specified intervals, e.g. monthly, hours, mileage. It is the best tactic for simple equipment that exhibits wear-out failure but can lead to unnecessary maintenance where failure did not occur (Mungani & Visser, 2014). Condition-based maintenance (CBM) is performed when considered necessary after inspection. However, it requires a considerable investment in technology, proper planning and careful choice of methods. Opportunity-based maintenance (OBM) is carried out when that opportunity arises. It mostly applies to non-critical parts of equipment. Design out maintenance (DOM) is a proactive policy aimed at improving the design of the system to reduce or eliminate the need for future maintenance. Nonetheless, formulating such strategies is not straightforward, and requires a structured framework for decision-makers to be able to select the most appropriate strategies that are tailored for recurrent critical failures on equipment.

3.2 Risk assessment techniques

Techniques used in assessing risk can be qualitative, semi-quantitative and quantitative. Qualitative techniques define risk by significance levels such as low, medium or high, semi-qualitative methods use ranking combined with formulae, while quantitative methods use practical value estimates in the analysis and produce values for risk rating (Simmons et al., 2017; Valis & Koucky, 2009). Insufficient information, lack of data and human influence are some of the factors that may hinder a full quantitative risk analysis and lead to the application of semi-quantitative and qualitative techniques.

Checklist technique is a list of hazards developed as a result of past experiences to be used in risk identification. However, it is less detailed and only used where another technique has been applied. Toxicity analysis (TA) assesses the risk to humans, animals and plants when subjected to environmental hazards. Scenario analysis (SA) measures risk by forecasting future occurrences and estimating potential consequences. It considers past experiences to determine possible future scenarios. Business impact analysis (BIA) analyses how key disruptions can affect organizational business objectives. It identifies critical business processes; how disruptive events will affect them, and the capacity needed to manage the impact of the disruptions. Brainstorming is where a group of experts come together and discuss freely to identify potential failures, their consequences and mitigation action. The Delphi technique is similar to brainstorming with the distinct difference that experts express their opinion individually while viewing the other experts' opinion (Valis & Koucky, 2009). Whereas brainstorming encourages broad participation and increases ownership of conclusions, it is only applicable to simpler systems of low-level detail.

Failure modes effect analysis (FMEA) is a structured investigation of an equipment potential failures, their causes and consequences. It identifies potential failures and ranks them in terms of importance and criticality. FMEA is both qualitative and semi-quantitative. Traditional FMEA process involves determining the possible effects of the failure modes on a system and ranking them in terms of severity, rate of occurrence and ease of detectability whose product is the risk priority number (RPN). However, in the industry today, it is crucial to prioritize operational costs which the three ordinal indices of severity, occurrence and detectability cannot determine. Hence the concept of cost based FMEA. The fundamental consideration for cost-based FMEA in risk assessment is the computing of failure costs in a system which is made up the cost of detecting failure, repair costs and the cost of spare parts (Spencer & Rhee, 2003). Hazard and operability analysis (HAZOP) are a qualitative technique that uses guide words, e.g. high, low to show system deviation from the norm without the need for calculations or modelling. Its main advantage is that it is easy to learn with little need for academic qualifications (Simmons et al., 2017).

Event tree analysis (ETA) is a graphical technique for representing the sequence of events following a failure. It can be used qualitatively or quantitatively to model, calculate and rank risks. Ishikawa (fishbone) diagram is a root cause technique that clusters possible failure causes into broad categories. It provides clarity in the identification of causes through a pictorial display that enables consensus to be built on the most likely causes which can be further tested empirically. Causal mapping is a root cause technique that doesn't emphasize on categorization but rather the relationship between causes. A causal chain is developed, connecting the causes to determine the real cause of failure (Keith, Loustau, & Melin, 2011). "5 whys" is a more straightforward approach that focuses down one single causal chain, the cause of the cause, five times. However, since most problems do not have a single root cause, one would have to repeat the method asking a different sequence of questions each time to uncover multiple root causes. Decision trees are used to model possible outcomes when selecting maintenance policies to apply to the results of the failure root cause analysis. They start from an initial decision and model different pathways as a result of different decisions to be made. The graphical presentation of decision trees helps to communicate the reasons for the decision chosen (Valis & Koucky, 2009).

3.3 Deductions from literature

Checklists, brainstorming, HAZOP, TA, SA and BIA are qualitive techniques and simplistic in their analysis. Therefore, they are suboptimal in the analysis of numeric data. FMEA provides for both qualitative and quantitative analysis. However, as observed, traditional FMEA does not provide for failure cost analysis, a key element of failure consequence, for management decision making. Therefore, cost based FMEA that analyses both the ordinal indices of conventional FMEA, and the failure cost consequence was suited for the study. Moreover, the quality of raw data gathered was less applicable detailed root cause analyses required of ETA and causal mapping. On the other hand, the repetitiveness of “5 whys” rendered it inapplicable on a system such as a drilling rig that has many components. The Ishikawa technique was therefore selected to illustrate probable root causes while decision trees were used to map maintenance alternatives

4. METHODOLOGY

4.1 Research design

This research adopts a case study of the KenGen Olkaria Geothermal Project rotary drilling rigs equipment failure. It entails the structuring of the rig into subsystems and equipment, investigating their failure modes and selecting critical equipment. Objectives of the study were to carry out risk prioritization of critical rig systems using cost based FMEA and Pareto analysis, undertake root cause investigation of critical equipment failure modes and develop a maintenance policy decision framework to derive strategies that address the failure root causes. The flow is shown in Figure 1.

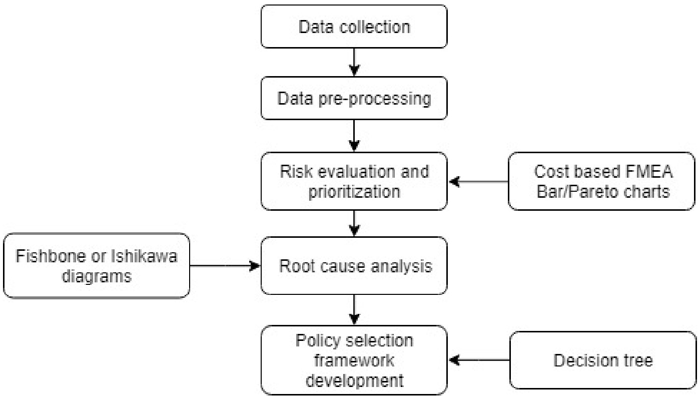

Figure 1: Schematic illustration of research methodology

4.2 Data collection and pre-processing

Data was collected from drilling and maintenance logs for nine geothermal wells drilled by KGN1 and KGN2 rigs. Raw data available was for date of failure, start of failure, end of the failure, failure description, well number, well depth and the rig name. The data was unstructured, handwritten in free text, difficult to analyze hence need for pre-processing. Firstly, the rig was structured into the main systems, which were hoisting, circulation, power, air package, rotary, instrumentation and control, lighting and auxiliaries. The systems were then disintegrated into constituent components as listed below. Failures were then linked to each component.

i. Hoisting system – drawworks, crown block, drill line, travelling block
ii. Instrumentation and control – camera, driller console, travelling block protector and instruments (drill watches, level sensors, indicators)
iii. Power system – generators, silicon-controlled rectifier (SCR)
iv. Rotary system – rotary table, top drive, grand rotating head, stripper rubber
v. Circulation system – mud pump, Kelly hose mud tanks, agitators, shelly shakers, submersible pumps, flow line, silencer
vi. Air package system – boosters, compressors
vii. Lighting and auxiliaries – lighting, catheads, power tongs, manual tongs, a blowout preventer (BOP)

Secondly, in order to carry out a full cost based FMEA, there was a need to compute failure cost data. Elicited from discussions with maintenance personnel the failure cost was derived as a sum of the downtime, spare parts and labor cost. The following equations were used to compute these costs.

$$Downtime = end\ of\ failure\ time - start\ of\ failure\ time \quad (1)$$

Downtime was useful in determining the downtime cost. Using the example of booster compressor failure for well OW-905 on 6th June 2014 to illustrate Eq. 1, failure commenced at 5.00PM and ended 7.00PM local time. The calculated downtime was 2 hours. Eq.2 below shows how the downtime cost was computed.

$$Downtime\ cost = Downtime \times Standby\ rate \quad (2)$$

Where standby rate was a fixed cost on the rig to cater for expenses incurred while not drilling such as meals, accommodation, fixed wages, electricity, laundry etc. To illustrate using the same example, downtime was 2 hours while standby rate for OW-905 was 69,737 Kenya shillings (Kshs) per hour. Applying Eq.2, the downtime cost yielded was Kshs 139,474. Furthermore, as evoked from consultations with maintenance personnel, labor cost was calculated as show in the following Eq. 3.

$$Labour\ cost = actual\ repair\ time \times number\ of\ technicians \times labour\ rate \qquad (3)$$

The actual repair time was the true time spent rectifying the failure separate from isolation time and time spent waiting for spares. The number of technicians was cited from maintenance records, while the labor rate was an average of the technician wages. Again, using the booster compressor example, the actual repair time was 2 hours, the number of technicians were 2 and the labor rate was Kshs 1200. Therefore Eq. 3 yielded the labor cost as Kshs 4,800. Finally, the spare parts cost was the price of a new item where an old part was replaced. The prices were sourced from inventory records. Table 1 shows sample preprocessed data with failure cost. The preprocessed data was used in the next segment of risk evaluation and prioritization.

Table 1 Sampled preprocessed data

Date	System	Sub System	Equipment	Description	Downtime (hour)	Downtime Cost (Kshs)	Spare part	Spares cost (Kshs)	Repair time (Hour)	Technicians	Labor rate (Kshs)	Labor cost (Kshs)	Failure cost (Kshs)
15-May-14	rotary	top drive	quill	quill rotating failure	4	278,950.31			3	2	1,200.00	7,200.00	286,150.31
21-May-14	rotary	top drive	wash pipe	wash pipe leaking	6	418,425.46	seals	50,000.00	2	2	1,200.00	4,800.00	473,225.46
27-May-14	hoisting	drawworks	clutch	faulty clutch	7	488,163.03	diaphragm	50,000.00	3	4	1,200.00	14,400.00	552,563.03
28-May-14	auxiliary	BOP	BOP	defective BOP	2	139,475.15			2	2	1,200.00	4,800.00	144,275.15
29-May-14	power	SCR	SCR	SCR unit failure	16	1,115,801.22			10	4	1,200.00	48,000.00	1,163,801.22
31-May-14	circulation	mud pump	pump	replace pistons pump 1	4	278,950.31	pistons	100,000.00	1	3	1,200.00	3,600.00	382,550.31

4.3 Risk evaluation and prioritization

The cost based FMEA involved computation of failure rate of occurrence, downtime rate and failure cost rate. The rate of occurrence was the number of recorded failures per equipment to the total rig failures as illustrated by Eq .4

$$failure\ rate\ of\ occurrence = \frac{number\ of\ equipment\ failures}{total\ system\ failures} \times 100\% \qquad (4)$$

Using the booster compressor example above, equipment failures were 11 to 157 rig failures. Eq.4 therefore yields the failure rate of occurrence as 7%. The downtime rate, on the other hand, was downtime hours of an equipment to the total rig downtime hours as shown in Eq. 5 below.

$$Failure\ downtime\ rate = \frac{equipment\ downtime}{total\ system\ downtime} \times 100\% \qquad (5)$$

Again, citing the booster example, the equipment downtime was 29 hours to 771 rig downtime hours. Eq. 5 therefore yields the downtime rate as 3.8%. The failure cost rate as shown in Eq. 6 was the failure cost of an equipment to the total failure cost. Similarly, the booster failure cost was Kshs 2,179,668.23 while the total failure cost was Kshs 60,188,879.04. Therefore, the resultant rate as per Eq. 6 was 3.6%.

$$Failure\ cost\ rate = \frac{equipment\ failure\ cost}{total\ system\ failure\ cost} \times 100\% \qquad (6)$$

Results of the analyses were illustrated on bar and pareto charts and equipment with highest cumulative impact identified as critical and selected for root cause analysis.

4.4 Root cause analysis

The Ishikawa technique was used to investigate failure causes in the root cause analysis. Firstly, the process started with a brief description of the component, its function and mode of operation. Possible failure causes were then identified, through consultations with maintenance teams, and clustered in categories of Machine, Material, Methods, Measurements and People. These clusters were displayed pictorially on the Ishikawa diagram as shown in the following Figure 2. Critical causes were displayed in the upper zone of the diagram from left to right and less critical causes displayed in the lower zone of the diagram with the least critical cause in the far right of the lower zone.

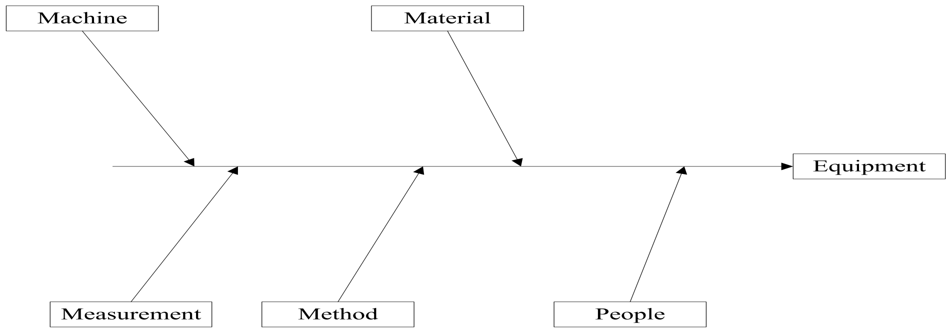

Figure 2: Ishikawa diagram illustration

4.5 Policy selection decision framework.

Further, elicited from consultation with maintenance personnel, a simplified decision tree shown in Figure 3 was drawn for maintenance tasks selection. The root node of the tree was a decision node to select critical and non-critical components. Equipment whose failure consequence posed a low safety risk and low failure cost were defined as non-critical. They were recommended for FBM. Equipment whose failure did not cause stoppage to operations were recommended for OBM. Equipment whose failure was detectable and eliminated through modification were recommended for DOM while those with undetectable failure that that can't be eliminated and exhibited age-related degradation with a repetitive pattern were recommended for TBM. Equipment with random failure pattern were recommended for CBM.

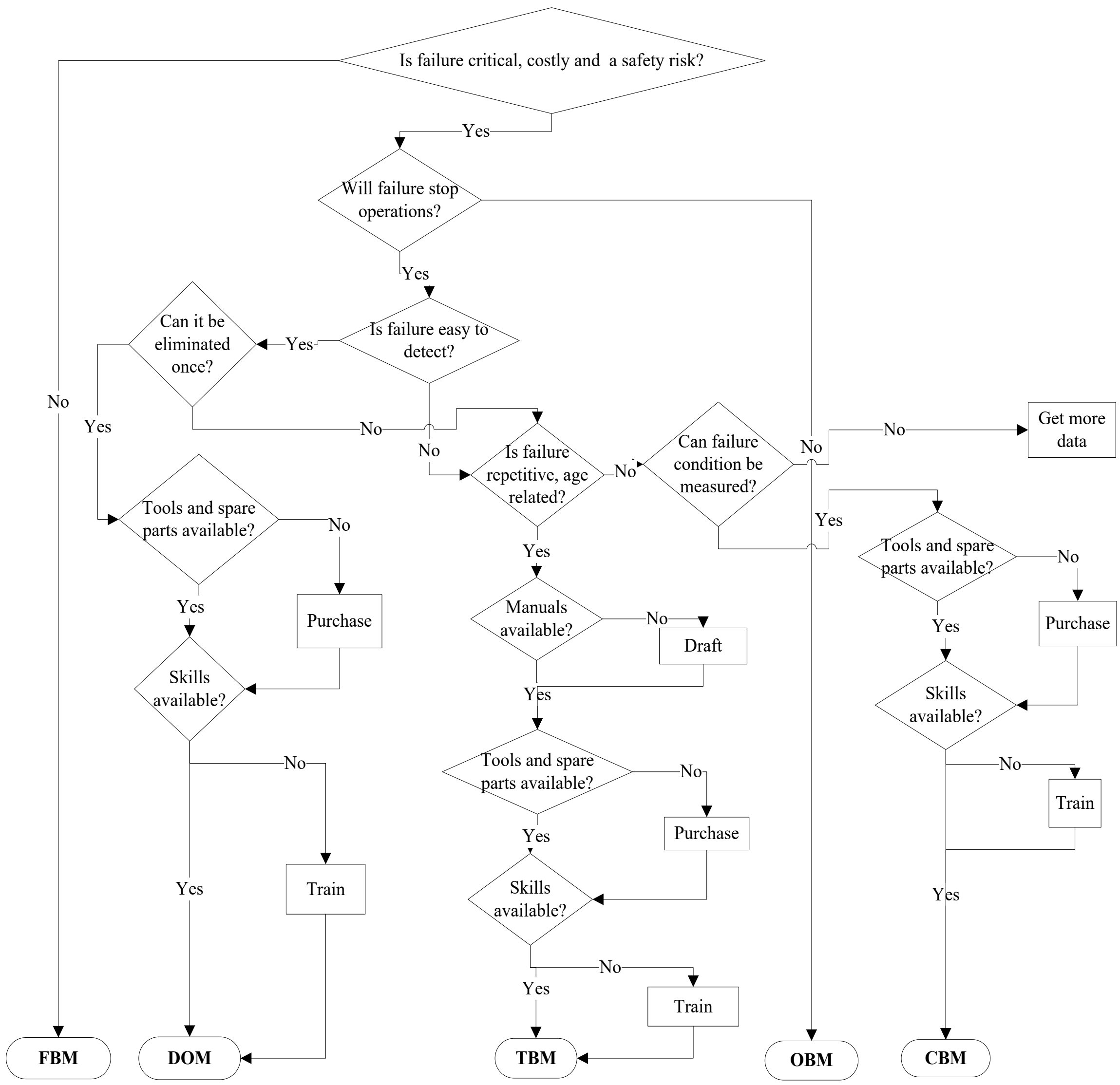

Figure 3: Decision tree for maintenance policy selection.

5. RESULTS

Figure 4 is a side by side illustration of the bar and Pareto chart results for the rig cost based FMEA analysis.

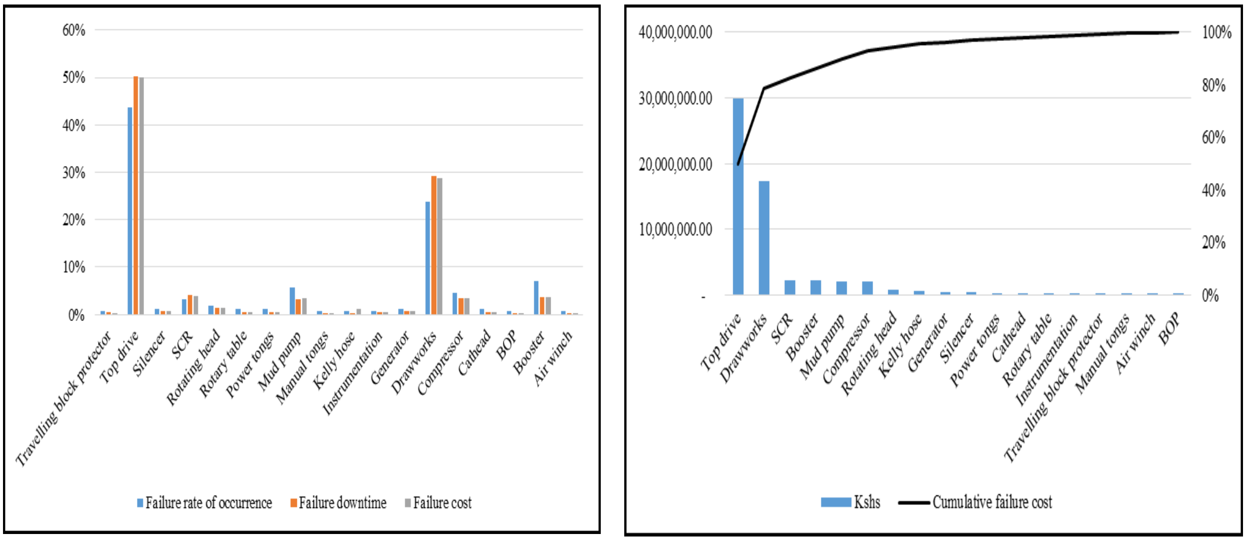

Figure 4: Rig failure cost based FMEA results

The top drive and drawworks had the highest failure impact at 43%, 50%, 50% and 24%, 29%, 28% for failure rate of occurrence, downtime and failure cost respectively. Manual tongs, instruments and the BOP had the least failure impact. Cumulatively both the top drive and drawworks accounted for over 80% of the failure cost. Therefore, the top drive and drawworks are the most critical rig components. This is understandable. The top drive is a modern, technologically advanced additional unit to the conventional rig. It has automated pipe handling functions that has the link-tilt, extend-retract, and 360º pipe rotation tasks for the driller to quickly engage and disengage while removing or restringing drill pipes thereby reducing risk, enhancing safety and increasing drilling speed. The drawworks on the other hand is the rig workhorse. It has a winch that operates with a drill line wound on a drum and runs to the top of the rig mast or derrick. At the top, the drill line runs on the stationery crown block, through the mobile travelling block and terminates as a permanently anchored deadline. As the drum rotates, it pulls the drill line tensioning against the deadline to create the up and down hoisting motion. The drum is driven by an electric motor via reduction gears and connected and disconnected by a clutch. When the drum is disconnected from the motor, its motion is stopped by a brake system.

Figure 5 shows further top drive and drawworks failure analysis. The electrical controls and robotics had the highest failure impact on the top drive while the clutch and brake were responsible for most drawworks failure.

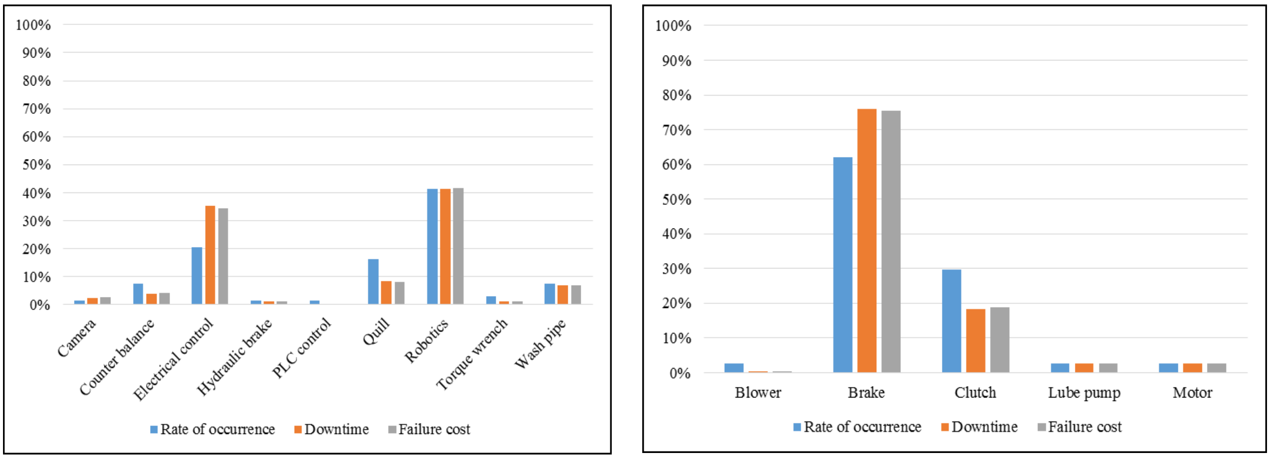

Figure 5: Top drive cost based FMEA analysis

The top drive robotics comprises of the grabber, link tilt and extend frame while the electrical controls are made up the variable frequency drive (VFD) and programmable logic control (PLC). Figures 6 and Figure 7 show the top drive robotics and electrical controls Ishikawa root cause diagrams. Most failure causes were machine related. Hydraulic hoses and tilt cylinders were hit by moving members causing fluid leakage and bending of cylinder shafts. Normal wear of hoses and studs resulted in hydraulic fluids leaks. Worn seals caused oil leakage that led to bearing overheat. Poor workmanship and improper handling of hoses and electric cables during installation caused breakage that led to fluid leaks and short-circuiting of cables. Overloading of cylinders by drillers caused bending of cylinder shafts. Material causes included the wrong design of bolts and pins that sheared under load and low-quality hoses that were easily damaged. Signal failures on the VFD and hydraulic power unit (HPU) were due to overheating caused by air conditioning failure and low hydraulic oil from the leaks

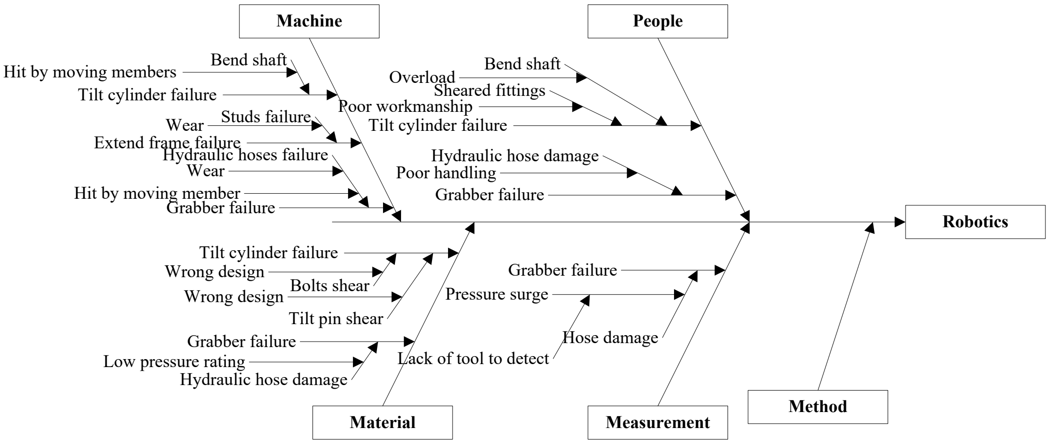

Figure 6: Robotics Ishikawa diagram

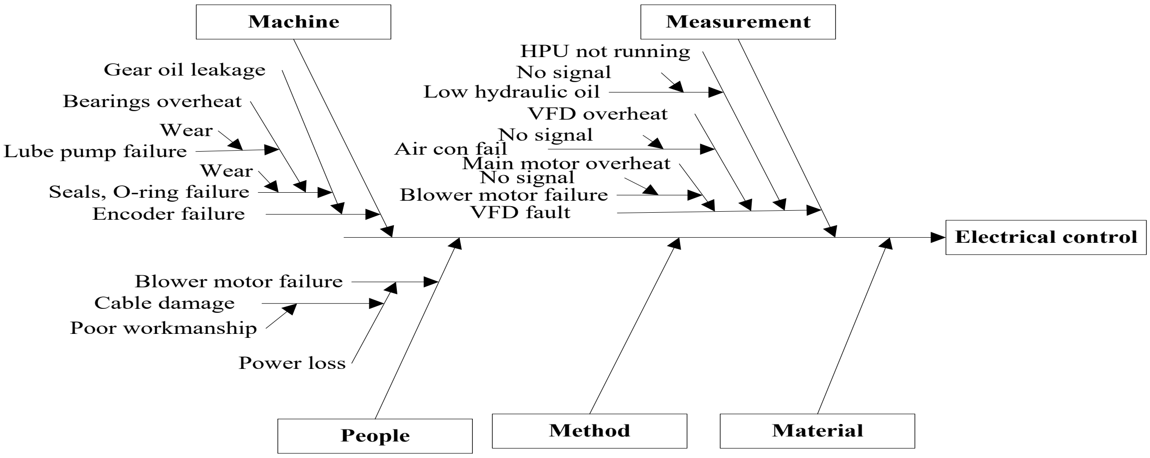

Figure 7: Electrical controls Ishikawa diagram

The drawworks brake consists of the hydraulic control that provides the hydraulic pressure to the calipers and brake unit, which is the power actuating mechanism that achieves the braking purpose. The clutch is the primary connection between the motor and the drum to produce torque required for rotary motion. Figures 8 and Figure 9 show the brake and clutch Ishikawa failure cause diagrams.

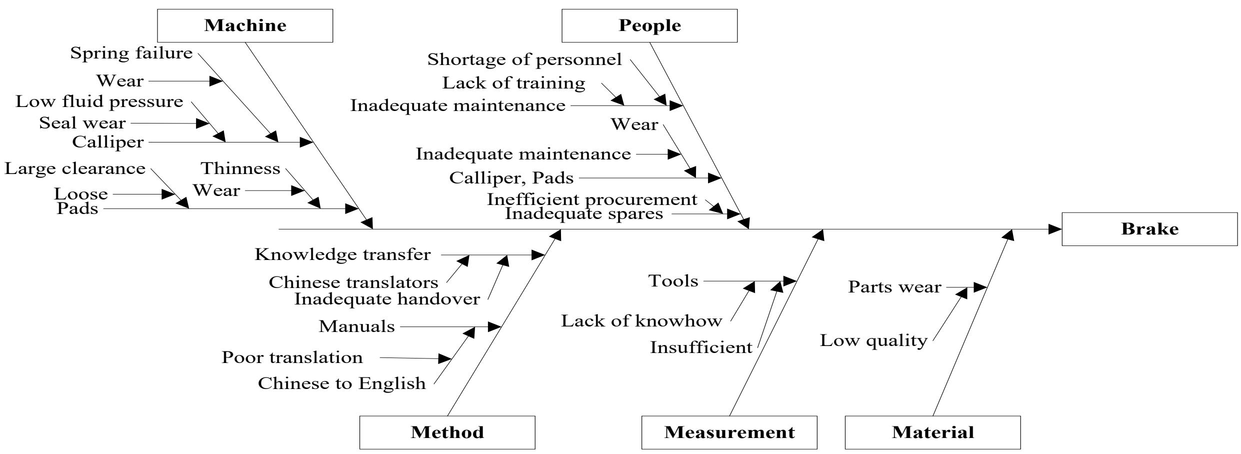

Figure 8: The Brake Ishikawa diagram

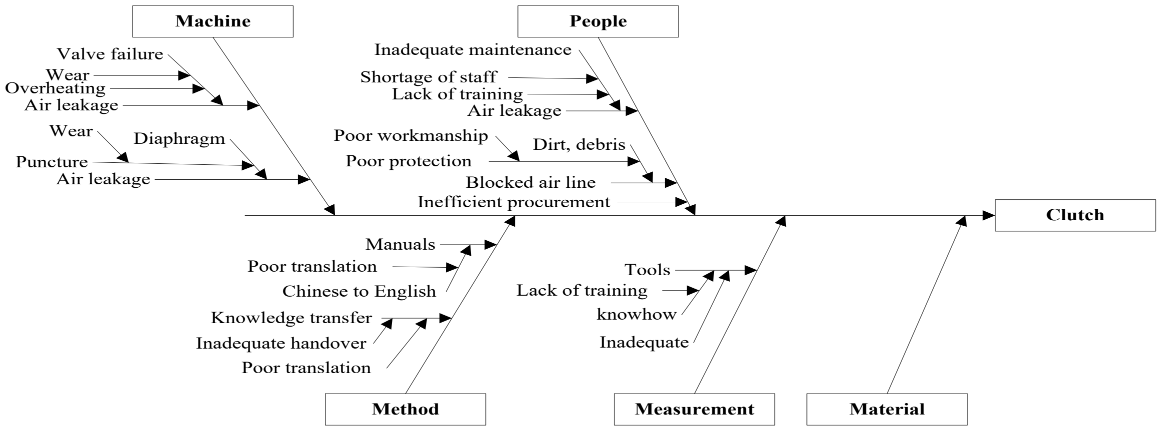

Figure 9: The Clutch Ishikawa diagram

Like robotics and electrical controls, most failure causes were machine related. Loose brake pads and worn-out diaphragms caused brake failure and clutch air leakages respectively. Worn seals and springs caused low fluid pressures that led to calliper failure. Overheating and wear of exhaust valves too caused air leaks. Bad workmanship such as leaving debris in airlines led to airline blockage, while poorly translation of manuals from Chinese to English were cited for incorrect execution of some maintenance procedures. These findings were discussed and shared in detail with maintenance teams.

5.1 Maintenance policy framework development.

Evidently, critical items from the prioritisation and root cause analysis were top drive robotics and electrical controls, and drawworks brake and clutch. OBM and FBM were ruled out as feasible alternatives. Robotics and electrical controls wear, and tear of hoses, seals and studs were recommended for TBM since they were repetitive and predictable. Random causes such as hitting by moving members, overheating and cable damage were recommend for periodic monitoring under CBM. Wrongly design of bolts and pins were best sorted by DOM while additional complimentary tasks of personnel training, close supervision and establishment of framework contracts to purchase critical spare parts were recommended. The brake and clutch loose pads, worn diaphragms, springs, seals and exhaust valves similarly were recommended for TBM, while overheating and air leakages were suited for CBM. Proper translation of maintenance manuals from English to Chinese was also cited and a critical task for maintenance efficiency. Figure 10 is an illustration of the summarised recommended maintenance actions.

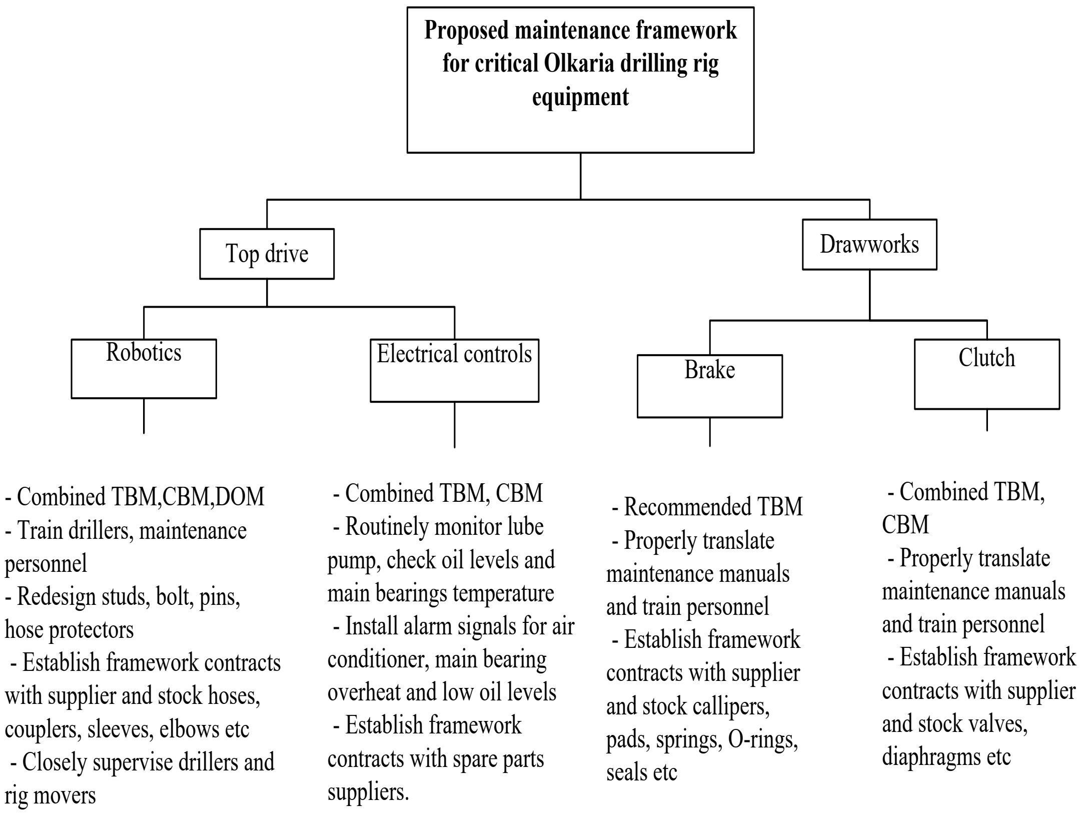

Figure 10: Proposed critical Olkaria rig equipment maintenance policy framework

6. CONCLUSION

This study set out to first identify critical equipment, secondly undertake root cause analysis of the critical equipment components failure and lastly, select appropriate maintenance policies to address the root causes. The study has shown that the critical rig equipment with highest failure impact was the top drive and drawworks, with robotics and electrical controls, brake and clutch as the critical units on the top drive and drawworks respectively. The study has also shown that the leading failure causes were machine-related wear and tear, overheating, loose parts and hitting by moving members. People causes included bad workmanship and poorly translated maintenance manuals. These causes can be remedied through a combination TBM, CBM and DOM policies with complementary actions as highlighted in the policy framework. Future work would include applying the developed methodology in this study to similar equipment failure analysis in geothermal drilling fields such as Menengai in the Kenyan rift and results evaluated. Moreover, modelling the rig subsystems, maintenance and spares policies and production while optimizing the various policies linking the maintenance and spares to the overall maintenance costs would offer more robust maintenance decision support.

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