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Development of Maintenance Management Strategy Based on Reliability Centered Maintenance for Marginal Oilfield Production Facilities

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Abstract

The present work adopted Reliability Centered Maintenance (RCM) methodology to evaluate marginal oilfield Early Production Facility (EPF) system to properly understand its functional failures and to develop an efficient maintenance strategy for the system. The outcome of the RCM conducted for a typical EPF within the Niger Delta zone of Nigeria provides an indication of equipment whose failure can significantly affect operations at the production facility. These include the steam generation unit and the wellhead choke assembly, using a risk-based failure Criticality Analysis. Failure Mode and Effect Analysis (FMEA) was conducted for the identified critical equipment on a component basis. Each component of the equipment was analyzed to identify the failure modes, causes and the effect of the failure. The outcome of the FMEA analysis aided the development of a robust maintenance management strategy, which is based on an optimized mix of corrective, preventive and condition-based monitoring maintenance for the marginal oilfield EPF.

Keywords

Criticality Analysis, Corrective Maintenance, Condition-Based Maintenance, Early Production Facility, Preventive Maintenance, Risk Priority Number

1. Introduction

Oil and gas exploration and development venture is highly capital intensive and involves a lot of uncertainties in terms of project development costs and revenue. A major deal breaker for exploration decisions is the reserves' size. In recent times, there has been increasing interest in oilfields that are initially considered unattractive for development due to technical, economic, or strategic reasons. These fields are referred to as Marginal Oilfields [1]. [2] highlighted the economic factors that classify an oilfield as marginal. These factors include high capital expenditure (CAPEX) and operating expenditure (OPEX) costs, unattractive revenue dependent on recovery factor, low production rates, technological constraints, Government regulations and policies, etc. However, advancements in petroleum engineering technologies such as 3-D seismic and opportunities for low CAPEX—phased development, among others, have favored interest in marginal oilfield development. While the low CAPEX requirement promotes the start-up of marginal field operations, many operators struggle to keep-up with operations due to the high OPEX, especially arising from the maintenance of the facilities.

Maintenance is critical to the healthy operations of any plant or facility. In the process industry where production operations run continuously round the clock, it is very essential to ensure that maintenance is properly planned to achieve a high level of equipment availability, because accidental stoppages result in substantial financial losses [3]. More so in the oil and gas industry, downtime resulting from improperly planned maintenance is shown to have a significant negative impact on the OPEX [4]. Downtime in the oil and gas industry is estimated to range between 5% to 10%, which is higher than other industries' average of 3% to 5%. This is because 90% of oil and gas companies are said to practice time based preventive maintenance, while about 5% to 20% adopt reactive maintenance [5]. According to [6] 40% of net operating expenses in the oil and gas industry is accountable to unplanned (reactive) and scheduled (time-based) maintenance, while unplanned plant shutdown accounts for nearly half of the overall losses of an oil facility. The impact of downtime is even more detrimental to the operations of a marginal oilfield, due to the compact size of field's production capacity. Therefore, it is incumbent to develop an efficient maintenance management strategy to ensure that the oilfield equipment are reliable, available and optimally operated. In this regard, this paper presents a Reliability Centered Maintenance (RCM) framework to support the maintenance management of a typical marginal oilfield production facility in Nigeria for a reduced OPEX and enhanced profit.

The concept of RCM was initially presented in theory as far back as 1969 by Nowlan and Heap [6], with the notion that failure distribution is not related to age and the frequency of performing maintenance. Thus, RCM is viewed as a technique that provides a bespoke approach to maintenance, bearing that facility equipment does not have the same level of importance to the operation and safety of the facility, therefore, such facility maintenance should not be generalized. Thus, RCM involves a systematic analysis of the functions and failures of a system to determine the appropriate maintenance to implement for such a system [7]. The outcome is a mix of specific-based maintenance techniques, which identifies equipment or components that should be run-to-fail, *i.e.*, corrective maintenance, those that require time-based preventive or scheduled maintenance, and more substantially, promotes the practice of condition-based (CBM) maintenance and predictive maintenance (PdM) [8].

RCM considers the functions of a system in normal or desired operating conditions and ways in which the system can fail to meet its desired or normal operating condition, *i.e.*, functional failure. Thereafter, the causes of the functional failures (the failure mode) are identified, together with the immediate effects and consequences of the failure. Opportunities to predict the failure are then explored, if not predictable, default actions are considered to prevent the failure [6]. Thus, in achieving a successful RCM, the following tools are essential: Failure Mode Effect (FMEA), Criticality Analysis, Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Logical Tree Analysis (LTA), and other risk-based decision-making tools [9].

[10] highlighted the attribute of RCM as an integrated approach that capitalizes on the collective strengths of several maintenance techniques applied optimally together, rather than independently, thereby maximizing facility and equipment reliability while simultaneously minimizing life-cycle cost. The author presented a methodology for RCM using a process steam plant as a case study; a significant reduction in OPEX, including spare parts and labor costs, were estimated, as well as a reduction of downtime by 80%. The limitation from this study is that the procedure only considered a single unit. Similarly, [11] presented a study on RCM procedures considering radical maintenance using an ethylene plant as a case study. The findings from the study facilitated a more efficient resource utilization and an improved maintenance program for the facility. While these techniques are adoptable for this current study, the key limitation is that the case study was not in the oilfield industry. [12] presented a comprehensive review of maintenance practices in the oil and gas industry, particularly in marginal oilfields. The major gap identified was the lack of study on the application of RCM to marginal oilfield maintenance. The study recommended that implementing RCM will potentially provide an efficient maintenance strategy for the marginal oilfield production facilities by reducing downtime and maintenance related OPEX [12].

This study hereby explores the techniques of RCM in developing an efficient maintenance strategy for marginal oilfield production facilities. A brief overview of a typical marginal oilfield production facility is presented in section 2, followed by the methodology used in developing the RCM-based maintenance strategy. The results were presented and discussed in section 4, and lastly, a conclusion section with key findings from the study and recommendations for further works.

2. Overview of the Production Facility in the Marginal Field Case Study

This study used a typical 10,000-barrels/day Early Production Facility (EPF) within the Niger Delta region of Nigeria as case study. The selection of the production facility was based on the data that EPF is the most common oil and gas production facility utilized by marginal oilfield operators in the country [2]. The case study EPF is designed to process up to 10,000 barrels of oil per day (bopd) and 20 million standard cubic feet (MMSCF) of gas (2000 GOR), produced from onshore oil wells within 500 - 3000 meters of the production facility. Stabilized crude oil from the EPF is transferred to temporary storage tanks onsite, after which the product is evacuated through the export facilities. Currently, the associated gas from the process is primarily disposed of by flaring. However, there are plans to process the gas for domestic use and export in the context of Nigeria's gas utilization policy.

The scope of this study was limited to five (5) units of the EPF based on the data available for the study, which include well control, gathering system, separation and stabilization, and process utilities, as shown in **Figure 1**.

The maintenance strategy currently adopted at the case study facility is predominantly time-based preventive across the entire facility. However, maintenance records from the facility also showed a high reliance on corrective maintenance in response to equipment failure or damage during normal operation.

3. Methodology

In this study, the RCM methodology adopted involved evaluating the EPF system to properly understand its functions and functional failures. This is followed by a systematic risk-based criticality analysis for the selected systems and an

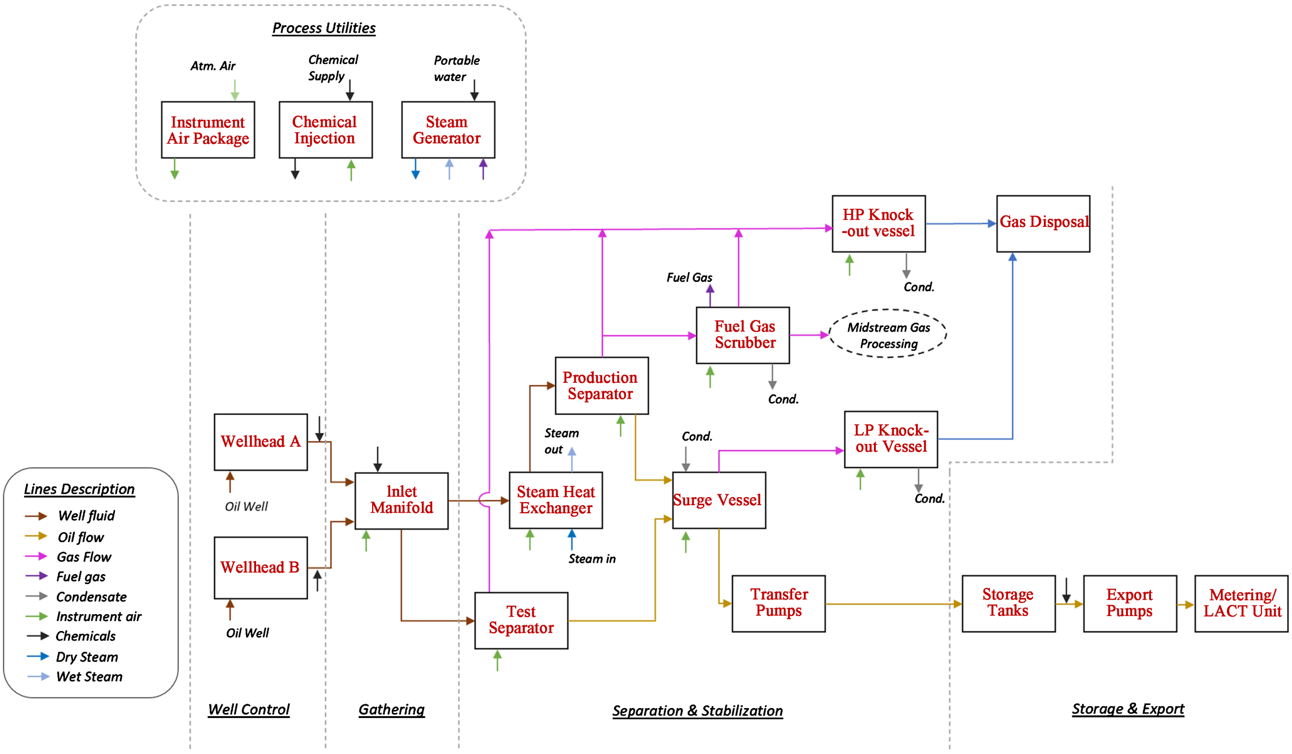

Figure 1. Functional block diagram of the EPF.

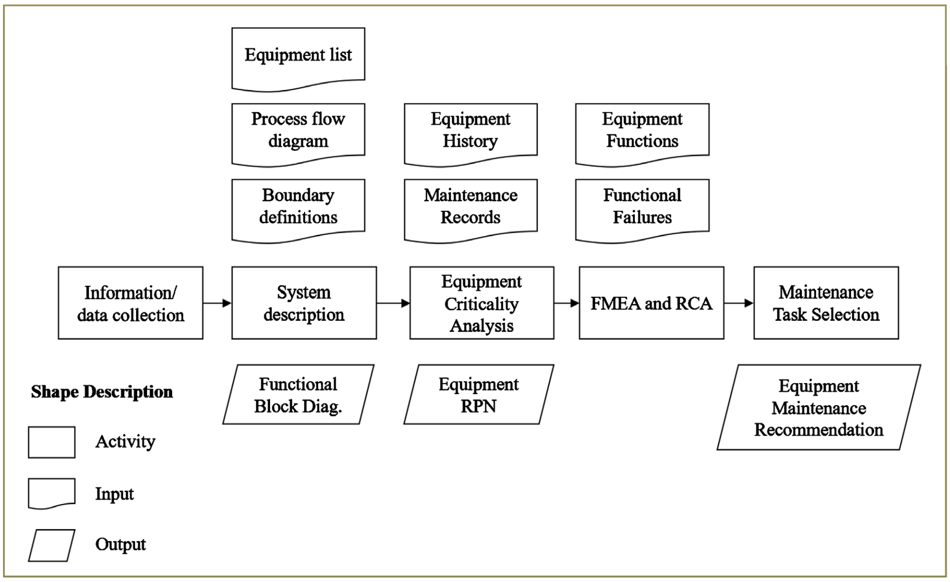

Figure 2. RCM methodology flow chart.

FMEA for maintenance task selection in that order. Figure 2 presents the flow diagram of the RCM methodology adopted.

3.1. Information and Data Collection

Relevant data required for the RCM were obtained from the case study facility by administering a technical questionnaire to key operations and maintenance personnel working at the EPF. This included the operations superintendent, maintenance lead and the health safety and environment (HSE) superintendents. Field visits were also conducted to verify the information/data provided. The technical questionnaire captured details such as facility overview, equipment list, equipment functions and functional failures (complemented with theories from literature), and equipment failures and maintenance records/history.

3.2. System Description

In addition to the overview of the case study facility presented in Section 2, further inputs including the equipment list, the process flow diagram (PFD) and the system "units" functions were used to obtain a comprehensive description of the facility. Based on the selected unit systems for RCM, clear boundaries were defined across the systems, as shown in the functional block diagram in Figure 1. The diagram shows the interactions of equipment within the same boundary and across different boundaries. This is important for the equipment criticality analysis to ascertain how an equipment failure can impact the overarching system.

3.3. Equipment Criticality Analysis

Equipment failure criticality analysis (FCA) is performed to evaluate the impact of equipment failure on the overall system. To achieve the FCA, equipment maintenance history and failure records were obtained from the case study.

Criticality analysis was used to evaluate the risk of a failure occurring against its consequences and the impact on the entire system or the business at large. The criteria of evaluation referred to as "risk factors" that were considered in this study included Production Loss (PL)—any failure event that can lead to production deferment or downtime of oil production, safety (S)—any failure event that could lead to injuries or fatalities, Environment (E)—any failure event that could negatively impact the environment either by pollution or damage, and Maintenance Cost (M)—direct cost associated with an equipment failure ranging from minor repairs to complete replacement.

A five-by-five (5 × 5) risk factor matrix evaluation procedure adapted from [11] was used to evaluate the risk factors based on five (5) levels of potential consequences. The failure criticality of an equipment with respect to a specific risk factor is given by the probability of failure (failure frequency) multiplied by the corresponding consequence, as shown in Equation (1). This yields a Risk Priority Number (RPN), also called Risk Rating, which determines the risk level of the failure. **Table 1** illustrates the evaluation of the RPN using a 5 × 5 risk matrix. The resulting RPN risk level is either low, medium, or high, as shown in **Table 2**.

$$\text{Probability of failure } P \times \text{Consequences } C = \text{RPN} \tag{1}$$

The description of the consequence level used in evaluating the 5 × 5 risk matrix is shown in **Table 3**, while the description of failure probability/frequency is shown in **Table 4**. The risk-based equipment criticality analysis was conducted with a team of experts from the case study facility. Inputs to the assessment included equipment list, maintenance cycle and equipment history/failure records.

Table 1. Illustration for the evaluation of RPNs using 5 × 5 risk matrix.

Risk Factor Consequence (C) Score	***Risk Factor*** Probability of Failure (P) Score				
	e	d	c	b	a
E	E × e	E × d	E × c	E × b	E × a
D	D × e	D × d	D × c	D × b	D × a
C	C × e	C × d	C × c	C × b	C × a
B	B × e	B × d	B × c	B × b	B × a
A	A × e	A × d	A × c	A × b	A × a

Table 2. Description of RPN risk levels for the risk factors.

Risk Level	**Risk Factors RPNs**			
	PL	**S**	**E**	**M**
Low	1 - 4	1 - 4	1 - 4	1 - 4
Medium	5 - 9	5 - 9	5 - 9	5 - 12
High	10 - 25	10 - 25	10 - 25	16 - 25

Table 3. Description of risk matrix consequnce levels.

Score	Consequence Level	Description for Risk Factors			
		PL	**S**	**E**	**M**
1	Minor	Less or no effect.	One or more minor injuries (first aid cases).	Impacts such as localized and short-term environmental degradation.	Minor maintenance cost or quick fix (less than \$1k).
2	Moderate	Impact on output or product quality.	One or more severe injuries.	Impact such as localized and long-term environmental degradation.	Moderate maintenance cost or repairs (\$1k to \$5k).
3	Major	Production deferment or shutdown up to 8 hours.	Physical disability or disfiguration.	Impacts such as short term and widespread environmental degradation.	Major maintenance cost or repairs (\$5k to \$10k).
4	Severe	Production deferment or shutdown 8 to 24 hours.	Accident leading to immediate fatality not more than one person.	Impacts such as long-term and widespread environmental degradation.	Complete overhaul (less than \$10k).
5	Catastrophic	Production deferment or shutdown more than 24 hours or damage to asset.	Large accident with more than one loss of life.	Persistent and landscape scale environmental impact or loss of a significant portion of a valued species.	Equipment replacement.

Table 4. Description of risk matrix consequnce levels.

Score	Occurrence in maintenance cycle
1	Once
2	Twice
3	Three times
4	Four times
5	Five times or more

The analysis included the maintenance engineering supervisor, the maintenance lead, and the Health Safety and Environment (HSE) superintendent. The resulting 5 × 5 matrixes are presented in Table 5, within the results and discussion section.

An "Initial Composite" risk priority number denoted by RPN' was obtained by multiplying all four RPNs (PL, S, E, M) for each piece of equipment as shown in Equation (2). The availability of redundancy or standby was also considered in evaluating the criticality of a piece of equipment, primarily in the area of production loss risk factor. A piece of equipment with a standby or redundant unit is expected to reduce the impact of failure only in production recovery. This is because the tendency of the failed unit to impact safety, the environment, and the maintenance cost remains the same. Thus, a "Residual Composite" risk priority number denoted by RPN_R was evaluated considering the availability of standby equipment where applicable. Equipment with redundancy is expected to contribute to the production loss by an operational rule of thumb of 10%, which accounts for the time taken to switch over from the failed equipment to its backup. The calculation for the residual composite RPN is expressed in Equation (3).

$$RPN' = PL' \times S' \times E' \times M' \tag{2}$$

where:

RPN'= Initial composite risk priority number;

PL'= Production loss risk priority number;

S'= Safety risk priority number;

E'= Environmental risk priority number.

Thus,

$$RPN_R = PL'(R) \times S' \times E' \times M' \tag{3}$$

where:

RPN_R = Residual composite risk priority number;

R = Availability of equipment standby.

And:

$$R = 0.1\kappa$$

where:

$\kappa = 1$: when there is an availability of equipment standby, and;

$\kappa = \frac{1}{0.1}$: when there is no availability of equipment standby.

After the residual composite risk priority number RPN_R is obtained, the next step is to determine the risk level or category for the RPN_R.

Recall the risk level description from Table 2 where the risk levels were defined as Low, Medium, and High for each risk factors obtained from the individual 5 × 5 risk matrix. The risk level for the RPN_R simply considers the upper limits of the individual risk factors' RPN. Multiplying these upper limit yields the range for the composite RPN for each risk level, this we termed Max Composite RPN for the respective risk levels.

Thus, the max composite RPN for each risk level is given by the expressions below:

$$RPN^- = PL^- \times S^- \times E^- \times M^- \tag{4}$$

where:

RPN^- = Max Composite RPN;

PL^- = upper limit of Production loss RPN;

S^- = upper limit of safety RPN;

E^- = upper limit of safety RPN;

M^- = upper limit of maintenance cost RPN.

The max composite RPN risk levels are therefore defined as follows:

Low: 1 to Low level max composite RPN

Medium: low level RPN^- +1 to Medium level RPN^-;

High: Medium level RPN^- +1 to High level RPN^-.

The Max composite RPN for the three risk levels are presented in Table 6 within the results and discussion section.

3.4. Failure Mode Effect Analysis

The FMEA is adopted to identify how the equipment at the production facility might fail and the relative impact of the identified failures. The main objectives of the FMEA are to the identification of the possible ways in which failure can occur (failure mode), their causes and the magnitude of the effects on the equipment or the system (failure effects) [13]. The FMEA, in the context of this study, was employed to analyze the equipment identified with medium and high failure criticality (residual risk priority number, RPN_R) to the system, thereby recommending appropriate maintenance tasks. The inputs to conducting the FMEA included the equipment functional failures that have occurred in the past, or those with the tendency to occur. Functional failures that have occurred were obtained from the facility equipment failure log.

The FMEA considered the equipment on a component basis. Each component of the equipment is analyzed to identify the failure modes, causes and the effect of the failure on the three dimensions described as follows

1) Local effect: component level;

2) System effect: equipment level, and;

3) Plant effect: effect of the failure on the overall EPF.

The outputs of the FMEA are contained in **Table 7** and **Table 8**, in the result and discussion section.

3.5. Maintenance Task Selection

Maintenance task selection for critical equipment is proposed to promote reliability-based maintenance. Thus, the aim is to identify equipment or components that can be maintained in the category of Corrective maintenance, Preventive Maintenance, and Condition-based maintenance that an artificial intelligence program can support. To achieve the maintenance selection, the outcome of the FMEA is further analyzed as shown in the flowchart in **Figure 3**.

Failures with low or no effect on component and system level are recommended for corrective maintenance. This is because such failures are usually associated with non-critical parts, which do not affect related parts or the system upon failure. In addition, the failure can be easily corrected with readily available spares at lower cost, compared to carrying out routine preventive maintenance, which according to [14], can be imperfect, thereby accelerating the failure mode.

Failures with medium system level impact were further analyzed using the 5 × 5 criticality analysis risk matrix. A low RPN_R indicates that the component can be placed under the corrective maintenance scheme, as with the previous case. If the RPN_R falls within the medium or high-risk rating, then the component can be considered for routine or time-based preventive maintenance. Similarly, if the failure has a high system effect and up to medium plant level impact, such should be considered for routine or preventive maintenance. Lastly, if failure poses a high risk to the plant, a Root Cause Failure Analysis (RCFA) is performed through a Fault Tree Analysis (FTA), to identify the type of failure exhibited by the component.

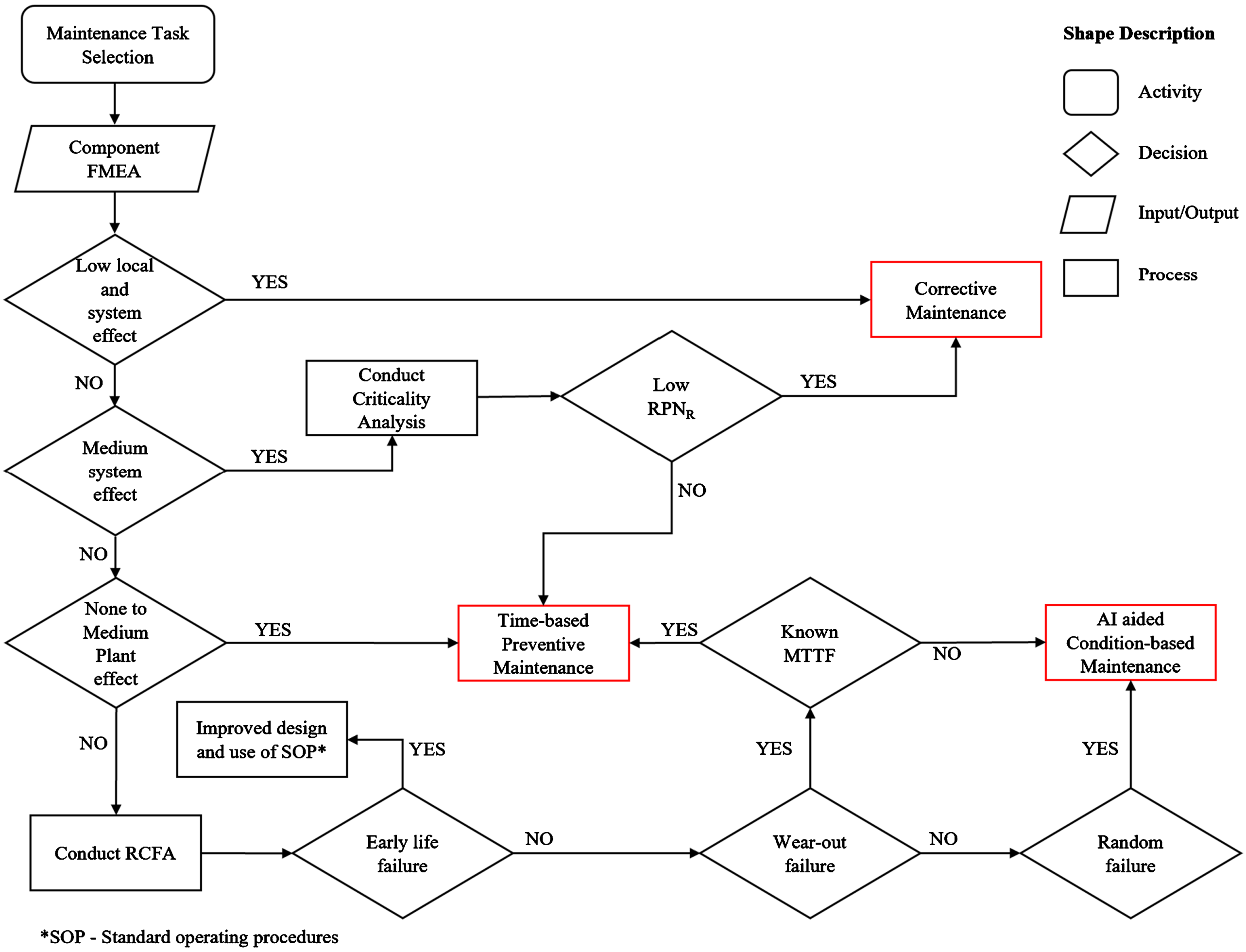

Figure 3. Maintenance task selection flowchart.

Failures are broadly categorized into three types in relation to the bathtub curve: early life failures, random (or constant failure), and wear-out failures [15] [16]. Early life failures are failures that occur at the early stage of equipment utilization, resulting from the faulty assembly, transportation or installation damage, or design error. Random failures are those that occur within the useful life of the equipment. They tend to have a random frequency and may be due to external events such as human error, improper operating procedures, overloads, etc. Reliability predictions and evaluation play a significant role in this type of failure. Lastly are wear-out failures, which increase towards the end-of-life of equipment or component.

Early life failures usually occur regardless of maintenance intervention; such failures fall in the category of reactive or run-to-fail. Engineering best practices in design, installation and commissioning are considered the best way to prevent such failures. Random failure is considered for CBM, particularly AI-based, to enable reliability monitoring and identification of potential failure before manifesting into functional failure. Wear-out failure, on the other hand, especially for non-repairable components, could have a pre-determined Mean Time to Failure

(MTTF), either from the experience of operating the equipment or from industry standards and guidelines. If the MTTF is known, time-based preventive maintenance is recommended; otherwise, such can also be considered for condition-based maintenance (CBM).

4. Results and Discussions

The risk matrix generated for the criticality analysis is shown in Tables 5(a)-(d), which was used to obtain the equipment failure risk priority numbers as described in section 3. The residual composite risk priority numbers (RPN_R) were categorized into respective risk level using the max composite RPN risk level shown in Table 6. A plot summarizing the equipment criticality analysis conducted is shown in Figure 4. The well control fixed choke assembly and the steam boiler unit were identified as equipment with the most failure criticality to the EPF. Other equipment with low RPNs were not considered for further analysis in this study; as such they were recommended for routine inspection and maintenance as per industry best practice and or OEM recommendations. Nonetheless, further system level-based RCM can be performed to address such equipment.

Further analysis was performed on the identified critical equipment using FMEA, CA and RCFA/FTA. As shown in Table 7, the steam boiler components fell mostly within the category of CM and PM. The most critical component was narrowed to the Pressure Safety Valve (PSV), which could lead to a catastrophe

Table 5. (a) "Production Loss" 5 × 5 Risk Matrix; (b) "Safety" 5 × 5 Risk Matrix; (c) "Environment" 5 × 5 Risk Matrix; (d) "Maintenacne cost" 5 × 5 Risk Matrix.

(a)

Production Loss **(*PL*)** Consequence Description	**Probability of Failure**				
	5 (occurs ≥ 5 times in a maintenance cycle)	**4** (occurs 4 times in a maintenance cycle)	**3** (occurs 3 times in a maintenance cycle)	**2** (occurs 2 times in a maintenance cycle)	**1** (occurs 0 - 1 time in a maintenance cycle)
Catastrophic (5) *Production deferment or shutdown > 24 hrs or damage to asset*	25	20	15	10	5
Severe (4) *Production deferment or shutdown 8 to 24 hrs*	20	16	12	8	4
Major (3) *Production deferment or shutdown up to 8 hrs*	15	12	9	6	3
Moderate (2) *Impact on output or product quality*	10	8	6	4	2
Minor (1) *Less or no effect*	5	4	3	2	1

(b)

Safety **(*S*)** Consequence Description	**Probability of Failure**				
	5 (occurs ≥ 5 times in a maintenance cycle)	**4** (occurs 4 times in a maintenance cycle)	**3** (occurs 3 times in a maintenance cycle)	**2** (occurs 2 times in a maintenance cycle)	**1** (occurs 0 - 1 time in a maintenance cycle)
Catastrophic (5) *Large accident with more than 1 loss of life*	25	20	15	10	5
Severe (4) *Accident leading to immediate fatality not more than 1 person*	20	16	12	8	4
Major (3) *Physical disability or disfiguration*	15	12	9	6	3
Moderate (2) *1 or more severe injuries*	10	8	6	4	2
Minor (1) *1 or more minor injuries (First Aid cases)*	5	4	3	2	1

(c)

Environment **(*E*)** Consequence Description	**Probability of Failure**				
	5 (occurs ≥ 5 times in a maintenance cycle)	**4** (occurs 4 times in a maintenance cycle)	**3** (occurs 3 times in a maintenance cycle)	**2** (occurs 2 times in a maintenance cycle)	**1** (occurs 0 - 1 time in a maintenance cycle)
Catastrophic (5) *Persistent and landscape scale environmental impact or loss of a significant portion of a valued species*	25	20	15	10	5
Severe (4) *Impacts such as long-term and widespread environmental degradation*	20	16	12	8	4
Major (3) *Impacts such as short term and widespread environmental degradation*	15	12	9	6	3
Moderate (2) *Impacts such as localized and long-term environmental degradation*	10	8	6	4	2
Minor (1) *Impacts such as localized and short-term environmental degradation*	5	4	3	2	1

(d)

Maintenance Cost (M) Consequence Description	Probability of Failure				
	5 (occurs ≥ 5 times in a maintenance cycle)	**4** (occurs 4 times in a maintenance cycle)	**3** (occurs 3 times in a maintenance cycle)	**2** (occurs 2 times in a maintenance cycle)	**1** (occurs 0 - 1 time in a maintenance cycle)
Catastrophic (5) *Equipment replacement*	25	20	15	10	5
Severe (4) *Complete Overhaul* (*>$10k*)	20	16	12	8	4
Major (3) *Major maintenance cost or repairs* (*$5k to $10*)	15	12	9	6	3
Moderate (2) *Moderate maintenance cost or repairs* (*$1k to $5K*)	10	8	6	4	2
Minor (1) *Minimal maintenance cost or quick fix* (*<$1k*)	5	4	3	2	1

Table 6. Composite RPN risk level.

Risk Level	RPN Upper Limit				Max Composite RPN	Max Composite RPN Risk Level
	PL^-	S^-	E^-	M^-		
Low	4	4	4	4	256	1 - 256
Medium	9	9	9	12	8748	257 - 8748
High	25	25	25	25	390,625	8749 - 390,625

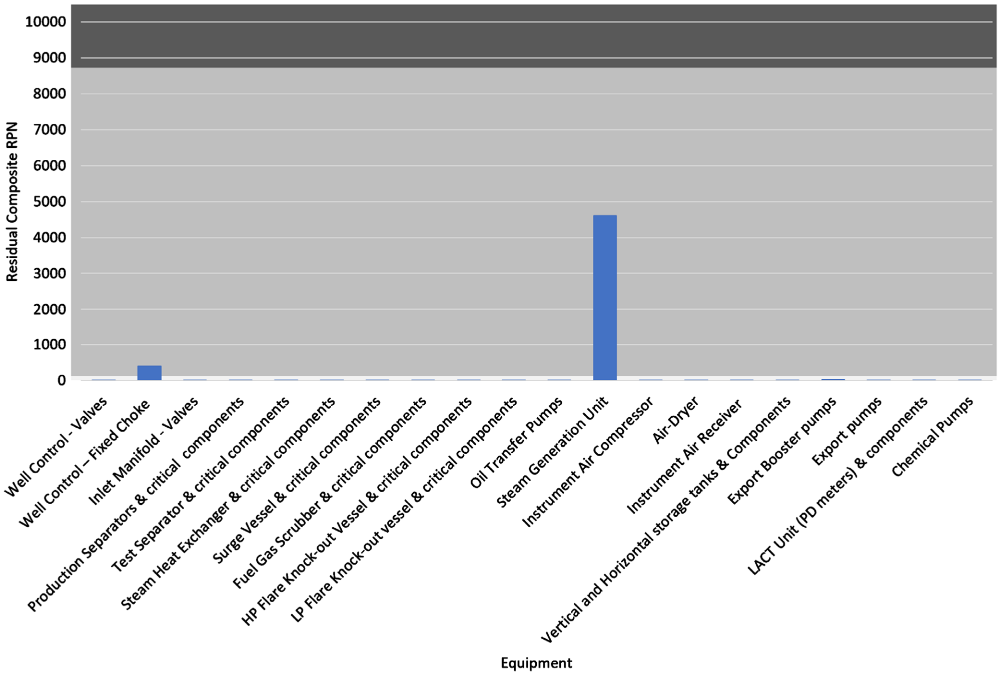

Figure 4. Plot of equipment failure criticality analysis.

Table 7. Steam boiler FMEA and maintenance task selection.

S/N	Boiler parts	Failure mode	Causes	Effect			CA “RPN”	RCA	MAINTENANCE TASK
				Local	System	Plant			
1	Boiler valve actuator	Failure to open	No signal from solenoid	Low effect	Low - Steam system lockout	No effect	-	-	CM
		Stuck open	Low signal from solenoid	Low effect	Low effect	No effect	-	-	
2	Gas valve actuator	Fail to open.	Low pressure	Low effect	Low - Steam system lockout	No effect	-	-	CM
3	Gas monitoring Control	Burner starts up and goes to lockout	Excessive increases in pressure	Medium effect	Low - Steam system lockout/Operation sequence not completed	No effect	-	-	CM
4	Programming control LFL	Program malfunction	Power fluctuation/Surge, Ingress	Medium effect	Low - Steam system lockout	No effect	-	-	CM and appropriate surge protection design
		Fuel valve closed							
		Fuel gas pressure switch, limit pressure switches all closed							
		Air damper not actuated to open position							
		Absence of flame signal							
		Loss of flame signal during normal operation							
5	Photocell	No flame	Covered with dust/ oil	High Effect	Medium - Signal would not be sent to the LDF programmer for low and high flame to establish	No effect	Low	-	Routine inspection and/or CM
			Photocell blown out						
			Fault from its wire						
			Insufficient fuel under ignition condition						

Continued

6	Dual solenoid valve	Failure to energize	Coil burnt out	Low effect	Low - Steam system lockout	No effect	-	-	CM
7	Pressure control/Pressure Switch	Failure to operate	Inlet blocked with debris/moisture inside the switch	Low effect	Low - Steam system lockout	No effect	-	-	CM
8	Wind/high gas pressure switch	Shutdown burner	Increase in gas supply pressure	Low effect	Low - Steam system lockout	No effect	-	-	CM
9	Air pressure switch	No adequate air for combustion	Air damper not actuating to open position	Low effect	Low - Steam system lockout	No effect	-	-	CM
10	Servo motor	Failure to operate, Seizure	Power fluctuation/Surge, Burnt motor Ingress and aging	Medium effect	Low - Flame failure	No effect	-	-	CM and appropriate surge protection design
11	Ignition Electrode	No ignition	Ignition electrode setting incorrect Cracked electrode insulator	Medium effect	Low - Fan start and burner goes to lockout	No effect	-	-	CM
12	Fuel solenoid valve	Failure to operate	Power fluctuation/Surge	Low effect	Low - Boiler trip	No effect	-	-	CM and appropriate surge protection design
13	Type E25 Intermittent ignition transformer	No ignition	Ignition transformer fault	Medium effect	Low - Fan start and burner goes to lockout	No effect	-	-	CM
14	Ignition Transformer	No ignition	Lead disconnected or damaged	Medium effect	Low - Fan start and burner goes to lockout	No effect	-	-	CM
15	Forced draft fan motor and Frame	No flame	Incorrect rotation of burner motor Malfunction of flap	Low effect	Low - Flame failure	No effect	-	-	PM

Continued

16	Gas Solenoid valve	Failure to operate	Power fluctuation/Surge	Low effect	Low - Boiler trip	No effect	-	-	CM and appropriate surge protection design
17	Feedwater pump	Failure to operate, Seizure	Power fluctuation/Surge/Stuck pump or Burnt motor	Low effect	Medium - Steam system trip No supply of water into the boiler drum	No effect			PM and appropriate surge protection design
			Air trap				Medium	-	
			Incorrect rotation of feedwater motor						
18	Gas pressure Regulator	Failure to open	Blockage	Low effect	Low - Steam trip	No effect	-	-	CM
19	Check Valve	Failure to open	Back pressure	Low effect	Steam trip	No effect			CM
		Stuck open	Blockage		Low effect	No effect	-	-	
		Crackedvalve			Low effect	No effect			
20	Blowdown valve	Failure to open	Corrosion	Low effect	Medium - Stock of debris inside the boiler	No effect	Medium	-	PM
21	Pressure Relief valve	Failure to open	Defective spring/Corrosion	High effect	High - Explosion	High effect	-	Wear-out with industry guide on MTTF	PM
22	Chemical dosing pump	Pump trip/Seizure	Power fluctuation/Surge, Burnt motor or stuck plunger or impeller	Low effect	Medium - Increased Scaling	No effect	Medium	-	PM and appropriate surge protection design
23	Pilot burner nozzle	Flame failure	Blockage by carbon deposit or sludge	Low effect	Low effect	No effect	-	-	Routine inspection and/or CM

Continued

24	Diesel pump	Abnormal noise during operation/Seizure	Contaminated diesel fuel Rust inside the pump	Medium effect	Low effect	No effect	-	-	Routine inspection, CM and appropriate fuel filter design
25	Control panel	Electrical component damage Incorrect burner sequence Excessive fuel being fired (Rich burn)	Power fluctuation/Surge Programmer malfunction Defective gas regulator	Low effect Boiler Trip Boiler trip	Medium - Boiler hard-start/ Steam System Shutdown	No effect No effect No effect	Medium	-	PM and appropriate design
26	Combustion Room	Excessive Air (Lean burn) Faulty flame detector Combustion gas pass failure Combustion air very low	Defective clock programmer Dirt, corrosion, defective wiring Defective actuator Stuck partially closed valve	Boiler low performance Boiler Trip Boiler Trip Boiler Trip	Medium - Steam System Shutdown	No effect No effect No effect No effect	Medium	-	PM
27	Furnace	Hole in tube	Pitting, crack	Boiler low efficiency	Medium effect	No effect	Medium	-	PM
28	Boiler Shells	Pitting/Cracking	High oxygen in feedwater, Poor water treatment	Steam/ water leaks to fire chamber	Medium - Reduced flow/Blow out likely	Medium effect	-	-	PM
29	Boiler Tubes	Leaks	High oxygen in feedwater, Poor water treatment leading to pitting and holes	Steam/ Water leaks to fire chamber	Medium - Reduced flow/Blow out likely	Medium effect	-	-	PM
30	Fire Bars	Fracture	Insufficient Feedwater, Rich burn combustion resulting to abnormal combustion (detonation)	Low firing rate	Medium - Reduced steam buildup or generation rate	Medium effect	-	-	PM

Table 8. Wellhead choke FMEA and maintenance task selection.

S/N	Wellhead choke Parts	Failure Mode	Causes	EFFECT			CA "RPN"	RCA	MAINTENANCE TASK
				Local	System	Plant			
1	Choke Bean (or nozzle)	Erosion	Imperfect thread contacts of bean and housing High sand production Presence of corrosive agent	High—Choke bean damage	High—Choke assembly internal damage	High—Oil reservoir upset/ damage	-	Radom failure	AI Aided Condition-Based Monitoring
2	Choke body	Pin hole or leakage at welded joint	Defective equipment Presence of corrosive agent	High—Choke body damage	High—Choke assembly exterior damage	Medium	Medium	-	Pre-commissioning (pressure testing) PM

in the EPF facility in the scenario of failure or unavailability when required. There are industrial recommendations and statutory requirements on periodic inspections and recertifications of the PSV based on best practices. Thus, the PSV was recommended for PM. The result for the wellhead choke assembly, however, as presented in **Table 8**, showed that the equipment's main component, the choke nozzle, exhibits random failure tendencies, and when it occurs, it is difficult to identify by physical inspection because the failure is mostly hidden. Such occurs within the internals of the equipment [17]. This necessitates the need for close monitoring of the performance conditions. As a result, the wellhead choke was recommended for condition-based monitoring maintenance, while failures associated with the choke body can be addressed by appropriate pre-commissioning pressure tests and periodic integrity test post-commissioning.

5. Conclusion

The outcome of the RCM conducted for the case study EPF within the Niger Delta zone of Nigeria provided an indication of equipment whose failure can significantly affect operations at the production facility. The steam generation unit and the wellhead choke assembly. The result of the component level FMEA conducted on the equipment aided the development of a robust maintenance management strategy, which is based on an optimized mix of corrective, preventive and condition-based monitoring maintenance the EPF. The proposed maintenance management strategy has the potential to reduce OPEX because it reduces routine preventive maintenance, which subsequently reduces costs from spare parts, labor and risk of failure from imperfect preventive maintenance. Furthermore, it enables the maintenance team to identify non-critical equipment parts that can be run to failure and thereafter replaced or corrected, which saves costs on routine parts replacement and prevents imperfect preventive maintenance that could result in unprecedented damage to parts or equipment. Such parts are common within the steam generation unit. In addition, the wellhead choke's main component was identified to require condition-based monitoring maintenance because of the failure mode it exhibits, which is hidden in nature. This has the potential to cause a major loss to the plant's operation, specifically causing damage to the oil reservoir if failure is not immediately addressed. Therefore, the future research direction would be to integrate the CBM with Artificial Intelligence capabilities such that it can trend the performance data of the equipment and flag any case of deviation from the expected outcome.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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