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Reduction of Boiler Operational Cost in a Refinery Using Reliability Model: A Case Study of Port Harcourt Refinery.

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ABSTRACT

In this study, reduction of boiler operational cost in a refinery was performed using reliability model. The boiler system was selected for reliability modelling as it has significant impacts on the plant production performance. The failure mode effects and criticality analysis (FMECA) of the boiler system was examined, and a maintenance task was developed for the system. The exponential reliability method was employed to analyse the failure data collected from the maintenance logbook of Port Harcourt Refining Company to carry out reliability modeling on their boiler system for operational cost efficiency. Reliability centered maintenance (RCM) identified all the perspectives of failures in the boiler systems' function and employed the appropriate maintenance approach for each failure respectively. Broad based results showed that the RCM had great impact on the preventive maintenance (PM) tasks. The Run-To-Failure (RTF) frequency was reduced. The result showed that by carrying out the proposed RCM labour plan-the labour cost decreased from ₦169, 344, 000.00/year to ₦121, 872,000.00/year (approximately 28.03% of the total labour cost) and about 33.71% of the annual spare parts cost was saved with the proposed PM plan. "The downtime cost (DTC) of the plant boiler was investigated. The proposed PM task results indicated a saving of about 29% of the total annual downtime cost as compared with the current maintenance (RTF) plan." The maintenance program applied in this study could be adopted by production firms to improve upon the reliability and operational cost of their production equipment.

KEYWORDS: Reliability, Boiler, Maintenance, Cost, Criticality.

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1.0 INTRODUCTION

A steam boiler is one of the most critical investments that owners of oil refinery plant and distilleries must consider for their enterprise. A reliable steam boiler is a necessary component of any refinery or distillery. Boilers are utilized to give warmth to the lower part of modern refining segments in processing plants. They heat up the fluid from the lower part of a refining segment to produce fumes which are gotten back to the segment to drive the refining detachment. The warmth provided to the section by the re-kettle at the lower part of the segment is taken out by the condenser at the highest point of the segment. Kettle is a shut vessel wherein water or the liquid is warmed under tension (Navneet & Bhangu, 2018). The steam or hot liquid is then flowed out of the heater for use in different cycle or warming applications. The steam created by the boilers is additionally used to control turbines for power generation, blowers, and pumps. Being a particularly necessary piece of treatment facility in a refinery, it makes the requirement for boilers to be fit as a fiddle a basic part of plant uptime. A security valve is needed to forestall over compression and conceivable blast of an evaporator (Castanier *et al.*, 2005).

Taking into account the above uses of a boiler in a refinery, its failure in any case is not tolerable. These boilers might fail because of various reasons; Some of the principal reasons are:

i. Failures of mechanical/electrical security valves-If the pressure of the boiler rise above the required limit, these valves are released. There is a lead, which will dissolve and release the pressure.

ii. Failures of temperature sensors- In the event of these failures, metallic sensors which sense the temperature, cut the electrical supply reaching the boiler and stops its work.

iii. Failures because of non-supply of water in the boiler. If water is not provided, air inside the boiler will get heated and will cause an impact on the boiler.

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The oil and gas industry are one of the most important sectors in terms of economic growth in Nigeria. Management of oil and gas processing industries are focusing on strategies of predicting failures and their system maintenance schedule as well as increasing productivity and efficiency of their production system. "The strong competitive environment between companies to secure business and the current world financial crisis are forcing organizations to explore ways to reduce operating costs. A popular approach to reduce operating costs is to reduce expenditures on equipment failures and repairs" (Samuel *et al.*, 2018). Reliability analysis describes the logical relationship between the components (subsystems) of a system to analyse the effect of their failure on the performance of the system for an effective maintenance strategy (Stapelberg, 2009). If a series configuration system must perform its function successfully, all the subsystems must be in operation. "Reliability is the probability that a component, system, or process will function without failure for a specified length of time when operated correctly under specified conditions" (Itthipol *et al.* 2017; Feili *et al.*, 2013; Wang & Majid, 2000).

Recent literature shows that a lot of attention is paid to the problem of reliability of production system. Many authors are professionally engaged in risk and operability study in boiler system of the steam power plant, research review on reliability centred maintenance and study of failure of the steam tubes of boiler furnaces in Najebia power plant (Musyafa & Adiyagsa, 2012; Devaraj & Pradeep, 2016; Najim & Mohammed, 2011). Brown *et al.* (1999) examined a systematic and cost-effective method to improve distribution system reliability. Niels *et al.* (2017) studied reliability analysis of a hydraulic on/off fast switching valve. Agnihotri *et al.* (2008) studied reliability analysis of a system of boiler used in readymade garment industry. Endrenyi *et al.* (1998) studied a probabilistic evaluation of the effect of maintenance on reliability and Hossam *et al.* (2013) studied a computer-aided Reliability Centred Maintenance-based plant maintenance management system while Zhu *et al.* (2019) conducted reliability analysis of centrifugal pump based on small scale sample data. These studies, however, addressed the problem of maintenance, but in a limited way. They either considered only one deterministic maintenance (or availability) constraint.

Alexander and Sini (2016) studied the application of reliability analysis for predicting failures in cement industry. Their research entailed the use of reliability analysis for predicting failures of machines used in the cement industries and was done by evaluating machine down times data. Their research work was required by the need to precisely foresee failures of the machines utilized in the cement industry and think of a viable way, for preventive maintenance timetable and reducing downtime through developed numerical model for the machines. The failure frequency variation with time was determined and a regression analysis using least squares method was done.
Correlation was done to ascertain the suitability of linear regression of the data and to determine that, the independent variable is a good predictor of the dependent variable. The reliability model of the machines was accomplished by applying the downtimes and the regression analysis of the machines studied for a period of six years to the Weibull model. Two basic segments of the machines were distinguished: contributing an aggregate of 55 % of the personal time. It was deduced in their examination that the basic segments show the pattern of failure of the machines.
This refinery boiler system can generate 120 tons of steam per hour each (PHRC, 2020). "The steam or hot fluid is then circulated out of the boiler for use in various processes or heating applications in the refinery such as to provide heat: to the bottom of industrial distillation columns and to power turbines for power generation, blowers and pump." "Being such an integral part of refineries operations makes the need for boilers to be in proper working shape a critical aspect of plant uptime" (Sharma, 2005).

The specific objectives of this research were as follows:

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i.To analyze the failure mode effect and criticality index of the boiler system and their root causes in Port-Harcourt Refinery.
ii. To use exponential reliability model to determine the reliability of the boiler system in Port-Harcourt Refinery.
iii. To generate a maintenance plan that reduces the operational cost of boilers in the Port-Harcourt Refinery.

The gap in existing knowledge on the reliability of production system is that within the limits of the literature review, no research work applied reliability analysis for boiler operation in an oil refinery using exponential reliability distribution model. This research work addresses a suitable method of identifying and managing failures of boiler operation in an oil refinery using reliability distribution model which will give operators and managers the ability to study their system in a proactive manner, to determine and predict the time to failure of the boiler system, thereby curbing downtime and reducing operational cost.

2.0 MATERIALS AND METHODS

The materials used for this work include the company's corrective maintenance logbooks, the company's annual report sheets, manufacturers manual, failure data sheets for the boiler system, MATLAB computer program and Statistical Package for Social Sciences (SPSS) computer software.

The step wise procedure in carrying the research analysis for this study includes:

i. Firstly, extant literatures, journal, conference paper and publications bordering on exponential reliability method and steam boiler operations in steam power plant were extensively reviewed.
ii. Failure data comprising of Operating time (OT), Number of failure (OF) and Downtime (DT) was collected from the Port Harcourt refinery through direct observation and from operational record of the refinery for the reliability modelling of their steam power plant's boiler equipment.
iii. The MATLAB computer program is started with a computer interface and the exponential reliability model as culled from extant literatures was developed.
iv. Then the failure rate and repair rate functions of the system were determined as culled from extant literatures.
v. The mean time between failures (MTBF), mean time to repair (MTTR) and Availability formulas were inputted as culled from extant literatures.
vi. Inputting the failure data collected from the refinery into the MTBF, MTTR and Availability methods, the MTBF, MTTR and Availability parameters of the boiler system were determined.
vii. And inputting the determined MTBF and MTTR parameters into the established failure rate and repair rate functions the failure rate and repair rate parameter of the boiler were calculated.
viii. With the calculated failure rate parameter and boilers system downtime inputted into the established exponential reliability model, the reliability of the boiler systems was computed.
ix. Finally, the Statistical Packages for Social Sciences (SPSS) computer software was employed to analyse the calculated reliability indices of the boiler system, descriptively, from which a maintenance plan centred on the analysed reliability of the system was generated, which reduces the operational cost of boilers in the Port-Harcourt Refinery.

The equations for computing the various parameters are stated below.

a. Criticality Index of the Boiler

The criticality index for the various causes and mode of boiler failure is determined by:

$$Equipment\ Criticality\ (EC) = 40\%\ S + 40\%\ P + 20\% C \qquad (1)$$

where:
S = safety related effect on boiler
P = production related effect on boiler
C = cost related effect on boiler

b. Exponential Reliability Model

The boiler system for time between failures follows the Weibull distribution where t is the continuous random variable representing the failure time.

The Probability Density Function (PDF) of the Weibull distribution as given by (Ebeling, 2007)

$$f(t;\beta;\theta) = \frac{\beta}{\theta}.\left(\frac{t}{\theta}\right)^{\beta-1}.\exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \quad (2)$$

where:

t = hours of operation/ up time

θ = scale parameter of the Weibull distribution

β = the shape parameter.

When failure rate (λ) of the system is determined, the reliability R (t) and the unreliability F (t) of boiler system at the end of (*t*) hours of operation / up time from our exponential reliability model as given by (Ebeling, 2007)

$$R(t) = e^{-\lambda t} \quad (3)$$

$$F(t) = 1 - e^{-\lambda t} \quad (4)$$

where:

λ = Failure rate of the system.

t = time in operation of the system.

i. Mean Time between Failures (MTBF)

The MTBF is a basic measure of reliability for reparable items and is estimated by the total time in operation of the boiler system and its subsystems divided by the total number of failures (breakdowns) recorded within a specific investigation period. Mathematically (Ebeling, 2007)

$$MTBF = \frac{\sum t_I}{n} \quad (5)$$

Mean time to repair ultimately reflects how well the system can respond to a problem and repair it.

$$MTTR = \frac{\sum t_i}{n} \quad (6)$$

iii. Failure Rate (λ)

Failure rate is the probability of failure per unit time. It is the rate of occurrence of failures. It is the reciprocal of the MTBF /MTTF function and is given by (Ebeling, 2007)

$$\lambda = \frac{1}{MTBF} = \frac{n}{\sum t_1} \quad (7)$$

where:

$\sum t_I$ = the total running time in operation of the boiler system during an investigation period for both failed and non-failed items.

n = number of failures (breakdowns) of boiler system or its parts occurring during a certain investigation period.

iv. Repair Rate

Repair rate is the probability of repair per unit time. It is the rate of occurrence of repairs. It is the reciprocal of the MTTR function and is given by (Ebeling, 2007):

$$\mu = \frac{1}{MTTR} \quad (.8)$$

Where:

MTTR = Mean time to repair

v. Availability

The "availability" of a system is, mathematically, MTBF / (MTBF + MTTR) for scheduled working time. It is given by (Ebeling, 2007)

$$A = \frac{MTBF}{(MTBF + MTTR)} \quad (9)$$

$$\text{Or } A = \frac{T_O}{T_O + T_1} \quad (10)$$

where:

T_0 = Time that boiler system works.

T_1 = Time that boiler system does not work, include repair and maintenance time.

vi. Cost

Total maintenance cost = Average downtime cost rate/hr x Average downtime of the system/year.

Proposed saved cost = (current labour cost + current spare part cost) – (saved labour cost + saved spare part cost).

Total saved maintenance cost using proposed plan = % saved proposed cost x total maintenance cost

3.0 RESULTS AND DISCUSSION

The boiler system in the Port Harcourt Refinery was selected for reliability centred maintenance (RCM) analysis.

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3.1 Boilers' Reliability Modeling

The results for the reliability indices of the boiler in the study period from Year 2018 to 2019 are presented. The results were obtained using failure data from Port Harcourt refinery, and computer program for the reliability modelling and algorithm.

Table 1: Failure Data of the Boiler System in Port Harcourt Refinery Steam Power Plant (From 2018 to 2019)

Steam Boiler System	Number of Failure	Operating Time (hrs)	Downtime (hrs)	Total Available Time
70B-01	5	15, 863.905	648.015	16, 512.000
70B-02	9	15, 479.750	1032.250	16, 512.000
70B-03	7	15, 937. 884	574.116	16, 512.000
70B-04	4	16, 105. 873	406.127	16, 512.000

Table 2: Reliability Indices of the Boiler System in Port Harcourt Refinery Plant

Steam Boiler System	Operating Time (hrs)	Downtime (hrs)	MTBF (hrs/failure)	MTTR (hrs/repair)	Failure rate (failure/hr)	Repair rate (repair/hr)	Availability	Reliability
70B-01	15, 863.905	648.015	3172.781	129.603	0.000315	0.000772	0.9608	0.82
70B-02	15, 479.750	1032.250	1719.972	114.694	0.000581	0.000872	0.9375	0.55
70B-03	15, 937.	574.1	2276.84	82.016	0.000439	0.002190	0.9695	0.79

The mean time between failures (MTBF) of the steam boiler system in the refinery is represented in table 2. The results show that, with respect to the failure data presented in table 1, out of the four (4) boilers that make the boiler system in the refinery, the boiler 70B-04 has the highest MTBF with 4026.468 hours and boiler 70B-02 has the lowest MTBF with 1719.972 hours within the study period. It is represented graphically in figure 1. This result generated is in good agreement with results obtained in the works of Ahasan (2015); Dhananjay and Sudhir (2015); Devaraj and Pradeep (2016); Zhu *et al*. (2019).

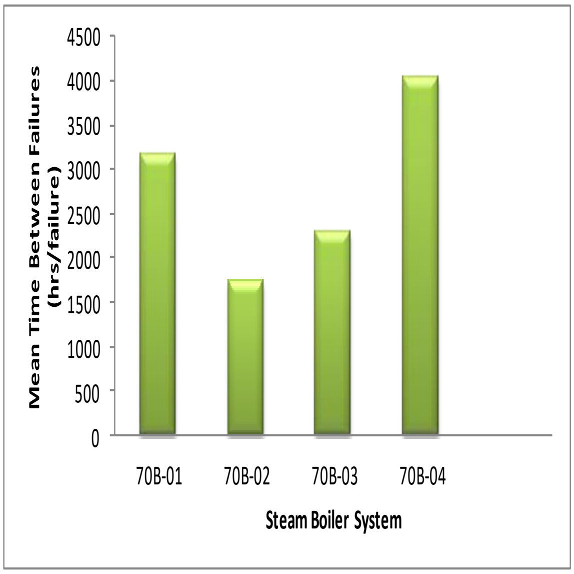

Figure 1: Boiler System's Mean Time Between Failures (MTBF)

The mean time to repair (MTTR) of the steam boiler system in the refinery is presented in Table 2. The results show that, with respect to the failure data in table 1, out of the four (4) boilers that make the steam boiler system in the refinery, the boiler 70B-01 has the highest MTTR with 129.603 hours and boiler 70B-03 has the lowest MTTR with 82.016 hours within the study period. It is graphically represented in figure 2. This result gotten agrees with the results obtained in similar works by Alexander and Sini (2016); Navneet and Bhangu (2018); Zhu *et al.* (2019).

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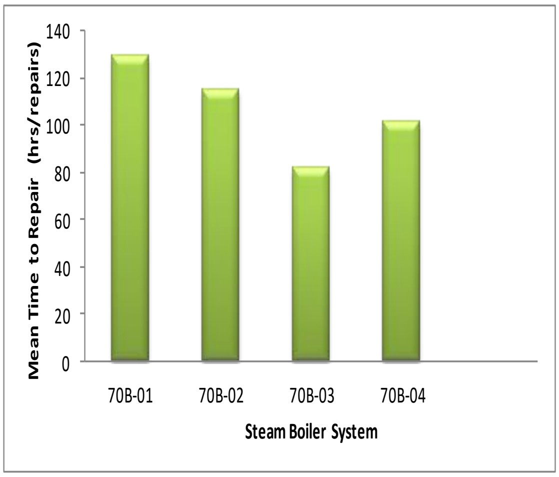

Figure 2: Boiler System's Mean Time to Repair (MTTR)

The failure rate of the steam boiler system in the refinery is presented on table 2. The results show that, with respect to the failure data in table 1, out of the four (4) boilers that make the steam boiler system in the refinery, the boiler 70B-02 has the highest failure rate at 0.000581failure/hr and boiler 70B-04 has the lowest failure rate with 0.000248failure/hr within the study period. It is graphically represented on figure 3. This result gotten is in good agreement with the results obtained in the studies by Dhananjay and Sudhir (2015), Ahmed *et al*. (2016) as well as Navneet and Bhangu (2018).

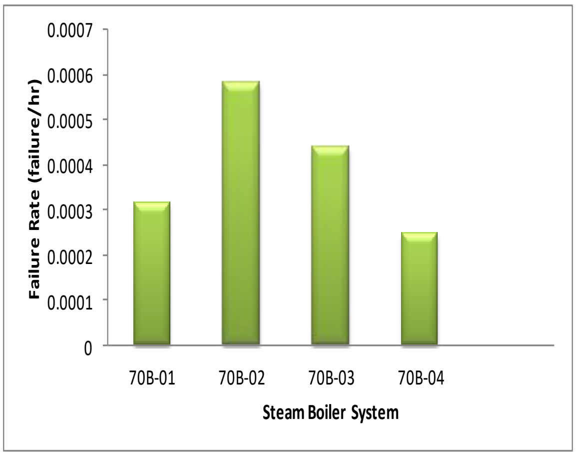

Figure 3: Boiler System's Boiler's Failure Rate

The repair rate of the steam boiler system in the refinery is presented in Table 2. The results show that, with respect to the failure data on table 1, out of the four (4) boilers that make the steam boiler system in the refinery, the boiler 70B-02 has the highest repair rate at 0.009849 repairs/hr and boiler 70B-01 has the lowest repair rate with 0.000772 repairs/hr within the study period. It is represented graphically in figure 4. This result gotten and the research approach correlates with the results obtained and the approach followed by Dhananjay and Sudhir (2015); Ahasan (2015) Alexander and Sini (2016); Devaraj and Pradeep (2016); Navneet and Bhangu, (2018); Zhu *et al.* (2019).

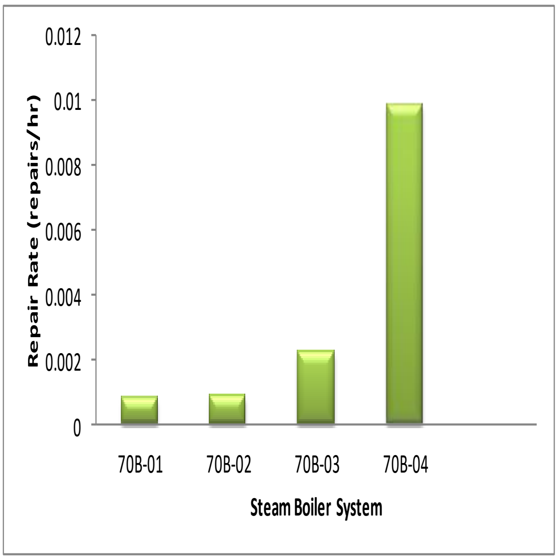

Figure 4: Boiler System's Repair Rate.

The availability of the steam boiler system in the refinery is presented in Table 2. The results show that, with respect to the failure data on table 1, out of the four (4) boilers that make the steam boiler system in the refinery, the boiler 70B-04 has the highest availability with 0.9754 and boiler 70B-02 has the lowest availability with 0.9375 within the study period. This result gotten and the research approach conforms with the results obtained and the approach followed by Ahasan (2015); Dhananjay and Sudhir (2015); Devaraj and Pradeep (2016); Alexander and Sini (2016); Ahmed *et al*., (2016); Navneet and Bhangu (2018); Zhu *et al.* (2019). It is graphically represented on figure 5.

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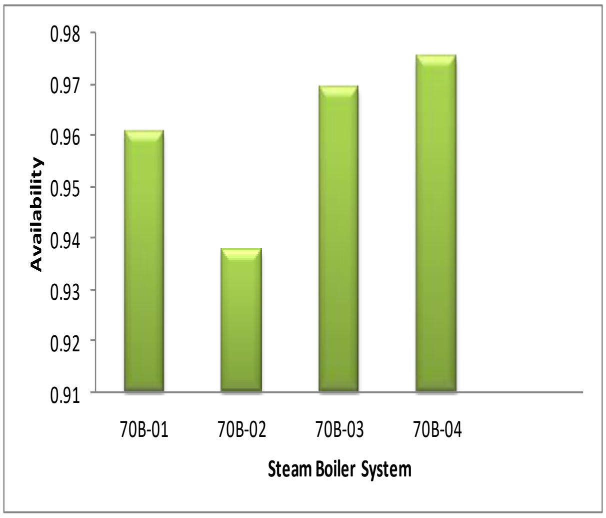

Figure 5: Boiler System's Availability (A)

The reliability of the steam boiler system in the refinery is presented in table 2. The results show that, with respect to the failure data in table 1, out of the four (4) boilers that make the steam boiler system in the refinery, the boiler 70B-04 has the highest reliability with 0.90 and boiler 70B-02 has the lowest reliability with 0.55 within the study period. This result gotten and the research approach agrees with the results obtained and the approach followed by Dhananjay and Sudhir (2015); Ahasan (2015); Alexander and Sini (2016); Devaraj and Pradeep (2016); Ahmed *et al*., (2016), Navneet and Bhangu (2018); Zhu *et al*. (2019). It is graphically presented in figure 6.

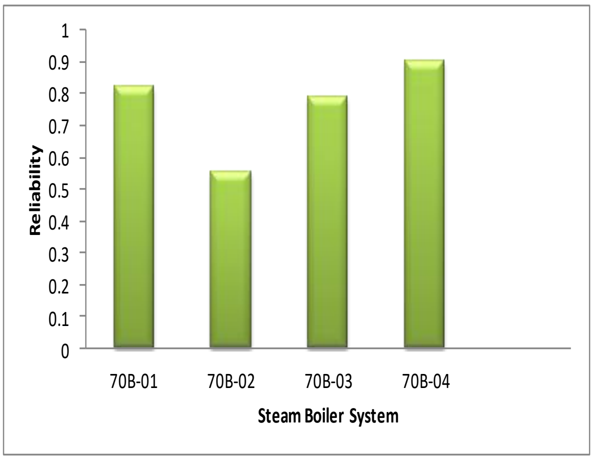

Figure 6: Boiler System's Reliability (R)

3.2 Modelling the Reliability of the Boiler System in Port Harcourt Refinery

The boiler system's failure rates against operating time, is shown in figure 7. The failure rate for boiler 70B-01 is 0.000315 failure/hour with a MTBF of 3172.781 hours, 0.000581 failure/hour for boiler 70B-02 with a MTBF of 1719.972 hours and 0.000439 failure/hour for boiler 70B-03 with a MTBF of 2276.841hours. The boiler 70B-04 has the lowest failure rate at 0.000248 failure/hr and MTBF 4026.468 hours. From the results on table 2, the reliability of the boiler 70B-04 is the highest at 90% after operating for 16, 105.873 hours, followed by the boiler 70B-01 whose reliability is 82% operating for 15,863. 905 hours. The boiler 70B-02 has the least reliability at 55% operating for 15,479.75 hours due to major system failures.

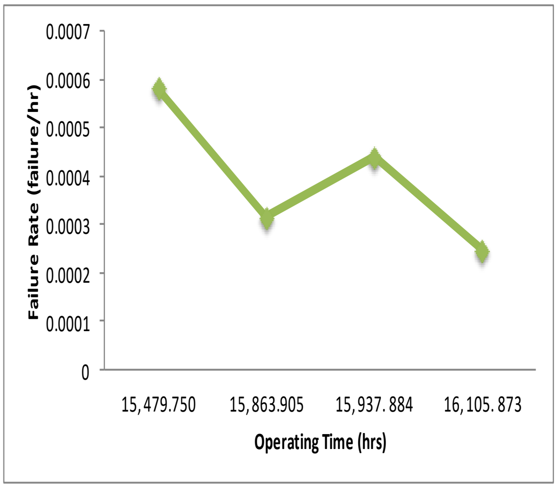

Figure 7: Boiler System's Failure Rate against its Operating Time

The maintenance strategy should be directed towards the item which is major contributor to the system failures as seen on the reliability column in table 2. Boiler 70B-02 has the least reliability after operating for 15,479.75 hours as shown in figure 8 below. It has the least reliability at 55% and highest failure rate at 0.000581 due to excess air, incorrect burner sequence, too much fuel being fired and dirty generating surface and dirty economizer which could be removed by

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promulgating simple routines such as cleaning generating surface, checking, and measuring the

diameter of the fuel opening holes inside burner, checking, and measuring the temperature of the stack gases to reduce its rate of failure.

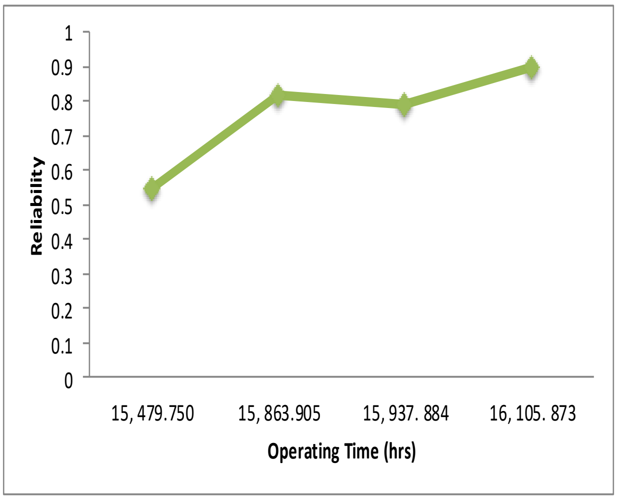

Figure Eight: Boiler System's Reliability against its Operating Time

3.3 System Root Cause Failure Analysis (RCFA)

Table 3: Boiler Root Cause Failure Analysis.

Failure Mode	Mechanism	Reason	Root Cause
Boiler efficiency	Smokestack	High temperature of stack gas	Too much excess air Dirty free sides
	Steam Pressure	Low steam pressure	Low water Excessive steam demands Poor combustion
	Combustion	Combustion gases entering fire room	Leakage through soot blower casing seal
Boiler tubes corrosion	Fuel	Fuel impingement on furnace walls and tubes	Incorrect viscosity, temperature, or pressure of fuel - Improperly made up atomize assemblies - water in fuel
		High fuel combustion	- Sudden change in steam demand - Too much or too little excess air

As shown in Table 3 above, root cause failure analysis for critical equipment in the refinery power plant (water tube boiler) is presented. The cause analysis (failure mode, reason, and root cause) for the most critical boiler in the refinery boiler systems which is the water tube steam boiler 70B-02 (it has the least reliability and highest downtime from the reliability analysis) is determined as tabulated.

3.4 Failure Mode and Effect Analysis (FMEA)

Failure mode and impact analysis is an apparatus that looks at likely system failure, assesses hazard, and suggest ways to prevent identified hazards from occurring. Failure mode and impact analysis help in identifying system failure.

3.5 Downtime Cost

Below is the percentage savings from the downtime cost compared to proposed maintenance plan.

i. Average downtime of the water tube boiler = 1330.254 hrs/year

ii. Total downtime from 2018 to 2019 for the 4 boilers = 2660.508 hrs

iii. Average downtime cost rate = ₦ 819, 699. 00 per hour (Port Harcourt Refinery Company Directory, 2020)

iv. Total downtime cost rate is ₦ 1, 186, 186, 161.546 per year

v. Total savings in maintenance cost using proposed plan = ₦ 57, 972, 000.00

vi. Proposed saving cost = ₦ 57, 972, 000

vii. Percentage proposed saving cost= 28.9%

viii. Total savings in maintenance cost using proposed plan = ₦342, 807,800.69

ix Maintenance cost using proposed plan is ₦ 843, 378,360.856.

4.0 CONCLUSION

The aim of this research is to reduce the operational cost of the boilers in a Refinery using Reliability Model. The reliability model applied reliability-centered maintenance (RCM) to reduce cost for Port-Harcourt Refinery Steam Power Plant in Rivers State, Nigeria. From the results, using the proposed maintenance plan, the total cost of maintenance of the boiler in the refinery was reduced by 28.9%. The results of the RCM technique applied on the refinery boiler generated the proposed preventive maintenance (PM) task and plan. Besides, the PM task comprised of on-condition and planned maintenance. The study showed that the RCM enormously affected the PM task and Run-To-Failure (RTF) recurrence diminished.

In view of the outcomes and discoveries, a maintenance policy is important to choose the frequency of maintenance and to decide how frequently maintenance should be done so that the equipment is highly reliable when required. Accordingly, the following recommendations are made to advocate effective reliability centered maintenance in the petroleum refineries.

i. It is imperative to have a preventive maintenance plan, for example, carrying out preventive maintenance only second or third month, since the preventive maintenance costs less than the breakdown maintenance.

ii. It is obvious that RCM has the potent of saving undue cost in scheduled maintenance and as such a more detailed and continuous study is needed for analysing the advantages acquired in terms of maintenance cost and functional adequacy for refinery steam power plant component on reliability aspects.

iii. The reliability model has the potential of identifying the critical part of the refinery boiler system that needs to be changed or repaired and should be adopted for use in the refinery.

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