Global Scientific JOURNALS

GSJ: Volume 10, Issue 5, May 2022, Online: ISSN 2320-9186
www.globalscientificjournal.com

Application of Condition-Based Maintenance Monitoring to a Palm Oil Processing Plant: A Case Study of SIAT Nigeria Ltd.

AMEKI, C., Barinyima Nkoi, and Okwu E. Isaac
Department of Mechanical Engineering, Rivers State University, Port Harcourt, Nigeria.
Mekisos4@gmail.com, +234(0)7033585532

ABSTRACT

This study is aimed at evaluating the maintenance management strategies of a palm oil plant using condition-based monitoring techniques. Failure rates of the component, downtime, the cost of monitoring equipment to conduct condition monitoring and the cost of labor, depreciation cost of the measuring equipment and the total cost of inspection for the machine were evaluated using data obtained from the palm plant for years 2017, 2018, 2019 and 2020. The result showed that the MTBF of the rotor component decreased from 2717.5 hrs in the first year to 468.6hrs in the fourth year, the MTBF of the bearing decreased from 1881.7hrs in the first year to 468.6hrs in the fourth year, the MTBF of the cracking pot decreased from 1558.7hrs in the first year to 292.9hrs in the fourth year while the MTBF of the drive shaft decreased from 5435hrs in the first year to 585.75hrs in the fourth year. The cracking pot had the highest of 0.00341 in the fourth year, inspection cost analysis was evaluated and was observed to be deprecating. The cost of measuring the equipment increased from 2800000 in the first year to 3550000 in the fourth year, the total inspection cost increased from 3708870.9 in the first year to 4995000 in the first year. It was recommended that there should be continuous review and improvement of the condition-based maintenance strategies to help the firm competes in the market and that the management should invest time, money and resources for the successful implementation of a good condition-based maintenance strategy.

KEYWORDS: Condition Based Monitoring, Processing Plant, Cracking Pot, Failure Rate, Downtime Cost

1. INTRODUCTION

In recent decades, production and its maintenance strategies are continuously evolving in processing plant for companies aiming to have a competitive production system. (Fraser *et al.* 2015). The growth of global competition has created remarkable changes in the way manufacturing companies operate.

These changes have affected maintenance and made its role even more crucial for business success (Kutucuoglu *et al.* 2001). To remain competitive, manufacturing companies must continuously increase the effectiveness and efficiency of their production processes. Furthermore, the introduction of lean manufacturing increases concerns regarding equipment availability. As a result, the demand for effective maintenance has significantly increased (Salonen, 2011).

Given ever-increasing global competitive pressures, it is essential that companies gain a better understanding of maintenance management programs to optimize both overall equipment effectiveness (OEE) and productivity (Fraser *et al.*, 2015). These pressures have given companies worldwide the motivation to explore and embrace proactive maintenance strategies in lieu of traditional reactive firefighting methods (Ahuja & Khamba, 2007).

The increased capabilities of manufacturing in measuring and monitoring will provide fewer machine breakdowns, smaller spare parts inventories, and reduced production and maintenance costs (Abele *et al.* 2010).

Condition Based Monitoring (CBM) is a set of maintenance actions based on the real-time or near real-time assessment of equipment condition, which is obtained from embedded sensors and/or external tests and measurements, taken by portable equipment and/or subjective condition monitoring (Butcher, 2000).

Martinelli (2007) studied the structure of optimal production policies under production-dependent failures with two failure rates, and later generalizes this to more general failure rate functions (Martinelli, 2005). Recent extensions include a system with two machines (Francie *et al.* 2014) and a run-based maintenance policy for the production scheduling problem (Lu *et al.* 2015). These studies assume that failure rates only depend on the age and the current production rate. Thus the production rate only affects the current failure risk and has no effect on the future failure behavior of the system.

In many practical situations, the production rate does not only affect the current failure probability but also results in permanent deterioration to the system, referred to as production-dependent deterioration. Zied *et al.* (2011) analyze production-dependent deterioration by accelerating the system’s aging proportional to the production rate. They consider a single-unit system with stochastic demand and optimize a block-based maintenance policy. Between maintenance actions, the adjustable production rate is used to balance inventory cost and failure risk. Ayed *et al*. (2012) extend the system to two units. De Jonge and Jakobsons (2018) consider block-based maintenance optimization for a machine for which the usage is random and that only deteriorates when it is turned on. These studies include production-dependent deterioration, but do not consider the potential of monitoring the actual deterioration level of the system.

It is well known that the use of condition monitoring can significantly improve operational decision making. For example, condition-based maintenance results in improved system reliability and lower maintenance costs (Kim & Makis, 2013).

A current trend in the literature is to study the use of condition monitoring for other operational decisions such as improved stock keeping of spare parts (Zhang and Zeng, 2017), managing rentals like cars (Slaugh *et al.*, 2016), and determining optimal production lot-sizes (Peng & Van Houtum, 2016).

In formulating maintenance models, the steps carried out include; Identifying the strategic goals of all stakeholders; Identifying the strategic goals for the maintenance department; Identifying relevant KPIs; Assessing the current state of maintenance; Set the goals for each KPI; Making an action plan

The aim of this research is to apply Condition-Based Maintenance Monitoring in SIAT palm oil production plant, in Nigeria, in order to enhance production. The specific objectives pursued were to; Examine the current state and effectiveness of the palm oil processing plant; Assess the causes of failure of the palm oil production plant; Apply Condition-Based Maintenance strategy to improve the operation of cracking machine of the palm oil plant; Investigate the cost effectiveness of carrying out the Condition-Based Maintenance of the plant.

2. MATERIALS AND METHODS

In this study a mathematical model was developed and data were obtained from the plant of a palm oil producing company, Rivers State in Nigeria, which its identity is protected in this work. This data include: cost of monitoring equipment, cost of inspection, repair cost, increase cost of running equipment above threshold limit and downtime of the equipment among others. There was also discussion with managers, supervisors, engineers and maintenance personnel on the implementation of condition based maintenance in the organization. Combinatorial optimization was developed and used as a method of solution. The result was validated using the model of Ben Daya and Duffuaa (1997).

Data for the failure analysis of the cracking machine was obtained from failure history of SIAT palm oil processing plant Rivers State. Four years secondary data was collected from the operational logs, maintenance records and historical data from the study area.

The four years data are maintenance and historical records from the year 2017 to 2020 respectively. These data include the number of tested units, number of failures, operation time and duration for a number of items such as rotor, bearing, cracking pots and drive shaft of the cracking machine. Also, the inspection interval of components, Salvage value of machine, the acquisition cost of the condition monitoring instrument and labor rate of the inspection personnel are also gotten from the study area.

2.1 Analytical Methods and Tools

The mathematical models consists of three parts: setup cost, failure cost and down time cost that may occur due to condition monitoring with an objective of determining the inspection time T_i for machine *I* as a multiple of the basic cycle so as to minimize the expected cost per unit time.

The following assumptions were made in the development of the model

i. The life of the machine is a random variable with probability density function *f*(t), where (t) is the life running time.
ii. The repair times are negligible and repair brings the machine back to an in-control-state.
iii. A cycle schedule is repeated every year.
iv. A constant inspection interval and its multiple to the basic cycle is assumed.

2.1 The Setup Cost

This cost consists of two parts: the cost of monitoring equipment to conduct CM and the cost of labour. This cost (Cbc) consists of the cost incurred at every basic cycle (Kallen & Nootwijk, 2006).

$$\text{Cbv} = \frac{P-SV}{nm} = Av \qquad (1)$$

2.2 The Down Time Cost

*Av*is the depreciation cost of the measuring equipment. It is spread over time. A straight-line depreciation method is assumed, P is the acquisition cost of the condition monitoring instrument, *t d* is amortization factor, SV is the salvage value, *nm*, is the planned number of years before replacement.

The total cost of inspection for the machine is given as (Yang *et al.* 2008)

$$\sum Cmi = \sum_{i=1}^{N} \frac{T}{Ti} \mathrm{a}_i \tag{2}$$

$$\sum Cmi = \sum_{i=1}^{N} \frac{T}{Ti} \mathrm{C_L t}_{inpectt} \tag{3}$$

where

$$\mathrm{ai} = \mathrm{C_L\, t}_{inpect} \tag{4}$$

CL= Labour rate of the inspection personnel

$\mathrm{t}_{inpectt}$= Machine *i*., N is the number of machines

(b) The downtime cost due to CM is given as:

$$\mathrm{C_{tdl,\, j+1}} = \sum_{i=1}^{N} \sum_{j=o}^{n-1} P_{\mathrm{Ltdmi}} \tag{5}$$

$j = 0,1,2 \ldots\ldots n - 1$

where $\mathrm{C_{tdl,\, j+1}}$is the down time cost due to condition monitoring of machine i in the interval j.P_L is the production/service loss per unit time and $\mathrm{T_{dm}}$ is the shut down time for CM inspection.

2.3 The Failure Cost

The total failure cost for N machines in a given system in a particular horizon is expressed as (Huynh *et al.*, 2013).

$$\sum C_{\mathrm{mi}} = \sum_{i=1}^{N} \sum_{j-o}^{nij} C_{\mathrm{j,\, j+1}} \tag{6}$$

where

$$\mathrm{C_{J,J+1}} = \frac{ri\left(1-e^{-\lambda t,j+1}\right)+si(ti,j+1)+siti,j+1e^{-\lambda,ti,j+1}-\frac{Si}{\lambda i}(1-e^{-\lambda iti\,,j+1})}{e^{-\lambda iti\,,j+1}} \tag{7}$$

$j = 0,1,2 \ldots\ldots n - 1$

For machine *I* between t_{io} and ti, $_{j+1}t$ the cost of failure at each $\mathrm{C}_{i,\,j+1}$ is calculated

An exponential distribution is assumed (Huynh *et al.* 2013).

$$fi(t) = \lambda i e^{-\lambda iti} \tag{8}$$

Where λi is the failure rate of the CM component in plant i. The failure rate is given as

$$\lambda i = \frac{1}{MTBF} \tag{9}$$

The mean time to failure is given as

$$MTBF = \frac{UT}{nft} \tag{10}$$

3. `RESULTS AND DISCUSSION

3.1 Computational Data and failure Analysis for Rotor Component

The rotor component of a cranking equipment of the palm oil plant was observed to be one of the equipment with regular breakdown. Appendix 1 shows the data collected for the rotor for a period of four years (study interval) which included the failure rate per year, operating time per week, mean time between failure (MTBF) and repair time to repair each breakdown per year.

Parameters	**Period (Year)**			
	1	**2**	**3**	**4**
Uptime (UT)	5435	4543	3243	2343
Study Interval (SI)	8760	8760	8760	8760
Meantime Between Failure (MTBF)(hrs)	2717.5	2271.5	810.8	468.6
Failure Rate (FR)	0.000367	0.000440	0.00123	0.00213
Downtime (DT)	8	6	12	15

Table 1 shows the data evaluated from the rotor component of the cranking machine using failure analysis.

Table 1: Analysis of Failure Data of Rotor Component

Looking at Table 1, from the computational rotor values, it is observed that there is a decrease in the uptime (operating time) from the 1st year to the 4th year. Also decreasing yearly is the mean time between failures, while the down time (DT) increases from the 1st year to the 4th year. There was also an increase in the failure rate form their 1st year to the 4th year. Consequently, from the table 4.1 it is seen that the mean time between failures (MTBF) is reducing from the first year of conditional monitoring of the component, from 2717.5hrs from the first year to

468.6hrs of the fourth year. This is an indication that as the year is increasing there is more interruption of operation of the equipment.

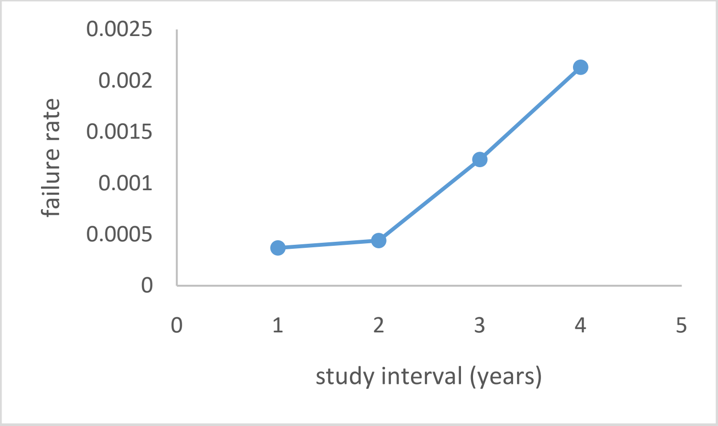

Figure 1: Failure Rate Against the Study Interval (4 years) of Rotor Component

The analysis of the research on Figure 1 shows that during production as the year increases, the number of failures for the rotor component was observed to be steadily increasing from the 1st year (2016) with a failure rate of 0.000367 until 4th year (2020) with a failure rate of 0.00213. The breakdown as a result of this same component also affected the production capacity of palm oil for these 4 years.

3.2 Computational Data and Failure Analysis for Bearing Component

The bearing component upon investigation showed that for the four-year period, there was a significant decrease in the operational time and increase in failure rate yearly as can be found on Table 2.

Table 2: Analysis of Failure Data of Bearing Component

Parameters	Period (Year)			
	1	**2**	**3**	**4**
Uptime (UT)	5435	4543	3243	2343
Study Interval (SI)	8760	8760	8760	8760
Meantime Between Failure (MTBF) (hrs)	1881.7	1514.3	1081.0	468.6
Failure Rate (FR)	0.0005519	0.0006603	0.000925	0.00213
Downtime DT)	9	6	6	10

Table 4.2 shows the data evaluated from the bearing component of the cranking machine using failure analysis. Observing at the Table 4.2, from the computational bearing values, it is observed that there is a decrease in the uptime (operating time) from the 1st year to the 4th year. Also decreasing yearly is the mean time between failures, while the down time (DT) decreases from the 1st year to the third year, then increases to 10 hours to the 4^{th}year. There was also an increase in the failure rate form their 1st year to the 4th year. Consequently, From Table 2 it is seen that the mean time between failures (MTBF) is reducing from the first year of conditional monitoring of the component, from 1881.7hrs from the first year to 468.6hrs of the fourth year. This is an indication that as the year is increasing there is more interruption of operation of the equipment and there is a reduction of performance of the cranking machine.

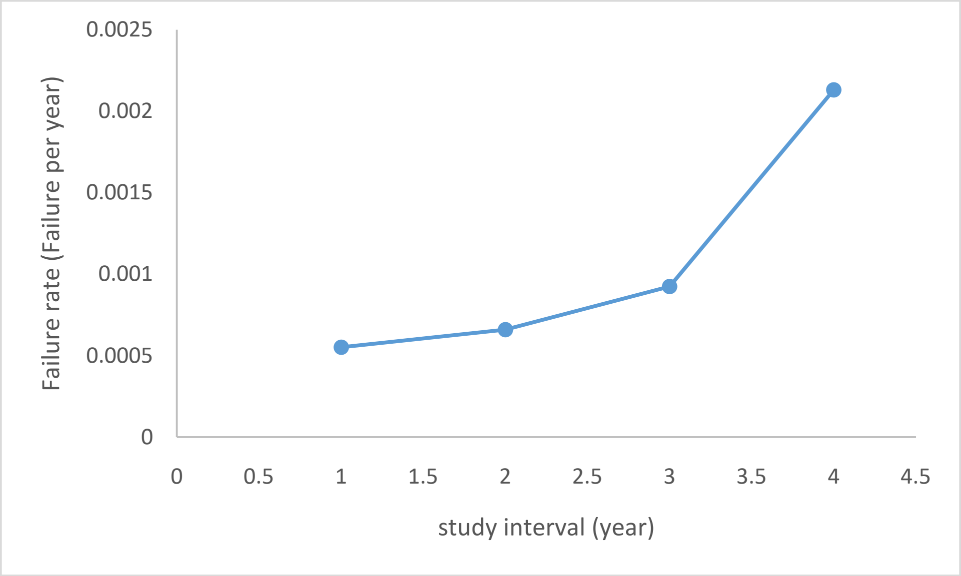

Figure 2: Failure Rate Against the Study Interval (4 years) of Bearing Component

The analysis of the research on Figure 4.2 shows that during production as the year increases, the number of failures for the bearing component was observed to be steadily increasing from the 1st year (2016) with a failure rate of 0.0005519 until 4th year (2020) with a failure rate of 0.00213. Also, figure 4.2 also shows that the failure rate of the rotor component is greater than that of the bearing component. The breakdown as a result of this same component also affected the production capacity of palm oil for these 4 years. An increase in failure rate also shows the condition of the equipment is very bad and it need an urgent maintenance.

3.3 Computational Data and Failure Analysis for Cracking Pot Component

The cracking pot component upon investigation showed that for the four-year period, there was a significant decrease in the operational time and increase in failure rate yearly as can be found on Table 3.

Table 4.3: Analysis of Failure Data of Cracking Pot Component.

Parameters	Period (Year)			
	1	**2**	**3**	**4**
Uptime (UT)	5435	4543	3243	2343
Study Interval (SI)	8760	8760	8760	8760
Meantime Between Failure (MTBF)(hrs)	1558.7	1335.7	540.3	292.9
Failure Rate (FR)	0.000735	0.000879	0.00185	0.00341
Downtime (DT)	12	12	12	16

Table 3 shows the data evaluated from the cranking pot component of the cranking machine using failure analysis. Observing at the Table 3, from the computational cranking pot values, it is observed that there is a decrease in the uptime (operating time) from the 1st year (5434hrs) to the 4th year (2343hrs). Also decreasing yearly is the mean time between failures (MTBF), while the down time (DT) decreases from the 1st year to the 4th year. There was also an increase in the failure rate form their 1st year to the 4th year. Consequently, from the table 4.3, it is seen that the mean time between failures (MTBF) is reducing from the first year of conditional monitoring of the component, from 1558.7hrs from the first year to 229.9hrsof the fourth year, which is lesser to that of the rotor and bearing component. This is an indication that as the year is increasing there is more interruption of operation of the equipment and there is a reduction of performance of the cracking machine.

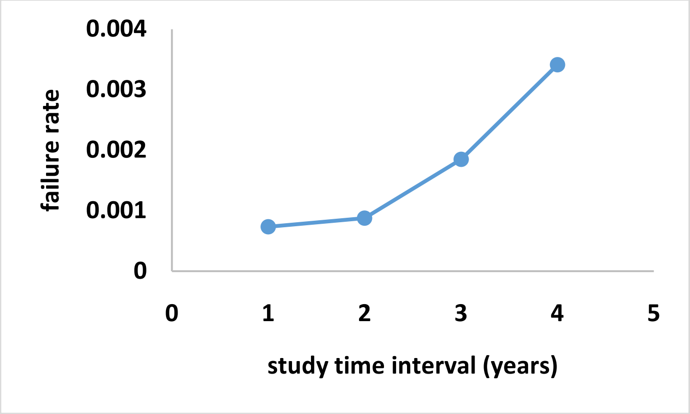

Figure 3: Failure Rate Against the Study Interval (4 years) of Cracking Pot Component

The analysis of the research on Figure 4.3 shows that during production of palm oil as the year increases, the number of failures for the cranking pot component was observed to be progressively increasing from the 1st year (2017) with a failure rate of 0.000735 until 4th year (2020) with a failure rate of 0.000879. Also, figure 4.3 also shows that the failure rate of the cranking pot component is greater than that of the rotor and bearing component. The failure as a result of this same component also affected the production capacity of palm oil for these 4 years. An increase in failure rate also shows the condition of the equipment is very bad and it need an imperative maintenance.

3.4 Computational Data and Failure Analysis for Component

The drive shaft component upon examination showed that for the four-year period, there was a significant decrease in the operational time and increase in failure rate yearly as can be found on Table 4.

Table 4: Analysis of Failure Data of Drive Shaft Component

Parameters	**Period (Year)**			
	1	**2**	**3**	**4**
Uptime (UT)	5435	4543	3243	2343
Study Interval (SI)	8760	8760	8760	8760
Meantime Between Failure (MTBF)(hrs)	5435	2271.5	810.8	585.75
Failure Rate (FR)	0.000183	0.0004402	0.00123	0.001707
Downtime (DT)	3	4	8	8

Table 4 shows the data evaluated from the drive shaft component of the cranking machine using failure analysis. Observing at the Table 4.4, from the computational drive shaft values, it was observed that there is a decrease in the uptime (operating time) from the 1st year (5434hrs) to the 4th year (2343hrs). Also decreasing yearly is the mean time between failures (MTBF), while the down time (DT) decreases from the 1st year to the 4th year. There was also an increase in the failure rate form their 1st year to the 4th year. Consequently, from the Table 4, it is seen that the mean time between failures (MTBF) is reducing from the first year of conditional monitoring of the component, from 5434hrs from the first year to 585.75hrs of the fourth year, which is lesser to that of the rotor, bearing and cranking pot component. This is an indication that as the year is increasing there is more interruption of operation of the equipment and there is a reduction of performance of the cranking.

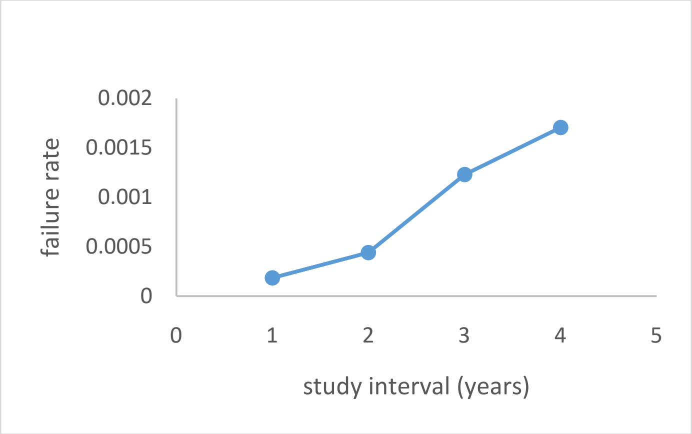

Figure 4: Failure Rate Against the Study Interval (4 Years) of Driving Shaft Component

The analysis of the research on Figure 4.4 shows that during production of palm oil as the year increases, the number of failures for the driving shaft component was observed to be progressively increasing from the 1st year (2016) with a failure rate of 0.000183 until 4th year (2020) with a failure rate of 0.001707. Also, figure 4.4 also shows that the failure rate of the driving shaft component is lesser than that of the rotor, cranking pot bearing component. The failure as a result of this same component also affected the production capacity of palm oil for these 4 years. An increase in failure rate also shows the condition of the equipment is very bad and it needs an imperative maintenance.

3.5 The Depreciation Cost of the Measuring Equipment Per Year

The result for the analysis of depreciation cost of the measuring equipment to conduct conditional monitoring and in cracking machine component is presented in Figure 5.

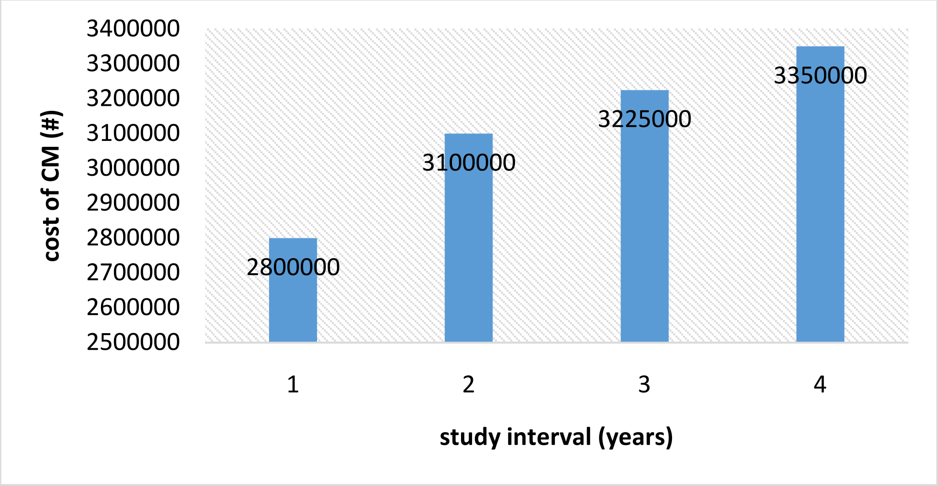

Figure 5: Depreciation Cost of the Measuring Equipment

Figure 5 shows the depreciation cost of measuring the machine components during conditional based maintenance monitoring of the cranking machine. From figure 4.5 it is seen that the depreciation cost of monitory increases from the first year #2850000 to the 4th year which is

#3350000. This shows that the value of the machine gets lower as the year is increasing so as it's performance rate is reducing.

3.5.2 The Cost of Inspection of Components per Month

The result for the analysis of cost of inspection of the cracking machine components during the process of conditional monitoring in cracking machine component is presented in Figure 6.

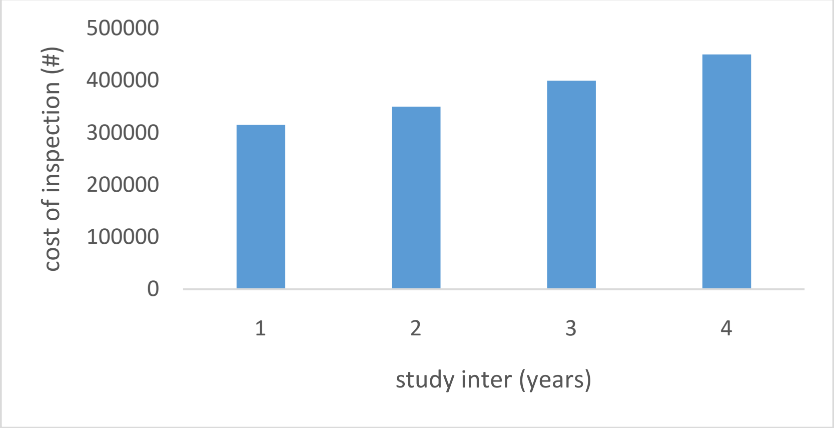

Figure 6: Cost of Inspection of Components per Month

Figure 6 shows the cost of inspection of component per month of the machine components during conditional based maintenance monitoring of the cranking machine. From Figure 6 it is seen that the cost of inspection of components per month increases from the first year #315000 to the 4th year which is #450000. An increase in cost of inspection per month shows that the performance rate of the machine is low and is an indication that the components need an adequate maintenance.

3.5.3 The Total Cost of Inspection for the Machine

The result for the analysis of cost of total inspection of the cracking machine components during the process of conditional monitoring of the cracking machine component is presented in Figure 7.

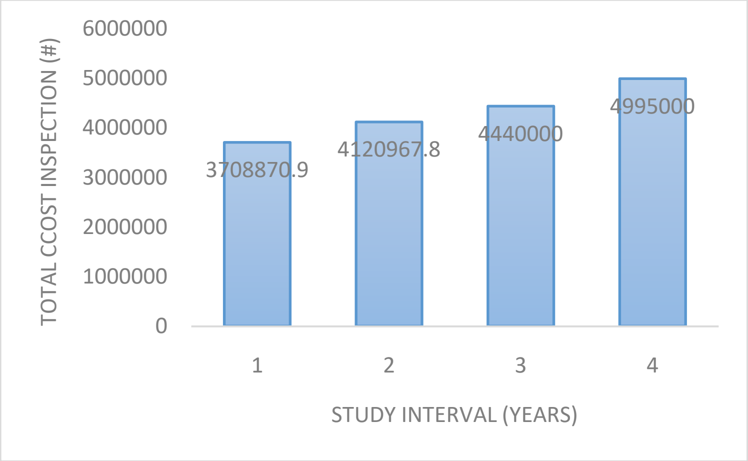

Figure 7: Total -Cost of Inspection of Components per Year

Figure 7 shows the total cost of inspection of component per year of the machine components during conditional based maintenance monitoring of the cranking machine. From Figure 7 it is seen that the total cost of inspection of components per month increases from the first year #3708870.9 to the 4th year which is #4995000. An increase in total cost of inspection per year shows that the performance rate of the machine is low and is an indication that the components need an adequate maintenance.

4. CONCLUSION

In investigation, mean time between failures (MTBF) of the rotor is reducing from the first year of conditional monitoring of the component, from 2717.5hrs from the first year to 468.6hrs of the fourth year. This is an indication that as the year is increasing there is more interruption of operation of the equipment. The breakdown as a result of this same component also affected the production capacity of palm oil for these 4 years.

The mean time between failures (MTBF) of the bearing is reducing from the first year of conditional monitoring of the component, from 1881.7hrs from the first year to 468.6hrs of the fourth year. The failure rate of the rotor component is greater than that of the bearing component. The breakdown as a result of this same component also affected the production capacity of palm oil for these 4 years. An increase in failure rate also shows the condition of the equipment is very bad and it needs an urgent maintenance.

The mean time between failures (MTBF) of the cracking pot is reducing from the first year of conditional monitoring of the component, from 1558.7hrs from the first year to 229.9hrs of the fourth year, which is lesser to that of the rotor and bearing component. The failure rate of the cranking pot component is greater than that of the rotor and bearing component. The failure as a result of this same component also affected the production capacity of palm oil for these 4 years.

The mean time between failures (MTBF) of the drive shaft is reducing from the first year of conditional monitoring of the component, from 5434hrs from the first year to 585.75hrs of the fourth year, which is lesser to that of the rotor, bearing and cranking pot component. The failure rate of the driving shaft component is lesser than that of the rotor, cranking pot bearing component. The failure as a result of this same component also affected the production capacity of palm oil for these 4 years.

The increase in depreciation cost shows that the value of the machine get lower as the year is increasing so as it performance rate is reducing. An increase in cost of inspection per month shows that the performance rate of the machine is low and is an indication that the components need an adequate maintenance. An increase in total cost of inspection per year shows that the performance rate of the machine is low and is an indication that the components need an adequate maintenance. The study recommended that; The cracking components should be readily available for replacement in the storeroom to reduce the downtime in a year as well as to enhance productivity; Management of palm oil plant has to invest in time, money and resources for a successful implementation of good CBM strategies. The firms should be dedicated and committed to cracking equipment maintenance. The firms should balance the maintenance strategies to get the optimum levels of corrective and preventive maintenance strategies. Routine conditional base maintenance activities are required.

5. ACKNOWLEDGEMENTS

The authors would like to thank the personnel of Rivers State University's Department of Mechanical Engineering for their technical assistance. We also appreciate the technical assistance provided by Engr. Rex. K. C. Amadi and Mr. Orokor, Allwell Chiyonu.

REFERENCES

Abele, E., Altintas, Y. & Brecher, C. (2010). Machine Tool Spindle Units CIRP. *Annals Manufacturing Technology*, 59 (2), 781-802.

Ahuja, I., & Khamba, J. (2007), “An Evaluation of TPM Implementation Initiatives in an Indian Manufacturing Enterprise. *Journal of Quality in Maintenance Engineering*, 13(4), 338-352.

Ayed, S., Sofiene, D. Nidhal, R. (2012). Joint Optimisation of Maintenance and Production Policies Considering Random Demand and Variable Production Rate. *International Journal of Production Research* 50(23) 6870–6885.

Butcher S. W. (2000). Assessment of Condition-Based Maintenance in the Department of Defense. Technical Report.

De Jong, E. (1997), Maintenance *Practices in Small to Medium Sized Manufacturing Enterprises (SMEs).* National Key Centre for Advanced Materials Technology, Monash University, Melbourne.

Francie, K. A., Jean-Pierre, K., Pierre, D., Victor, S., & Vladimir, P. (2014). Stochastic Optimal Control of Manufacturing Systems Under Production-Dependent Failure Rates. *International Journal of Production Economics* 150 174–187.

Fraser K., Hvolby H. H.& Tseng T. L. (2015). Maintenance Management Models: A Study of the Published Literature to Identify Theoretical Evidence. *International Journal of Quality & Reliability Management*, 32(6), 635-664.

Kim, M. J. & Makis, V. (2013). Joint Optimization of Sampling and Control of Partially Observable Failing Systems. *Operations Research.* 61(3), 777–790.

Kutucouglu, K. Y., Hamali, J., Irani, Z., & Sharp, J. M. (2011). A Frame Work For Managing Maintenance using Performance Measurements Systems. *International Journal of Production Management*, 21(1/2), 173-195.

Lu, Z., Cui, W. &Han, X. (2015). Integrated Production and Preventive Maintenance Scheduling for a Single Machine with Failure Uncertainty. *Computers & Industrial Engineering.* 80(6), 236–244.

Martinelli, F. (2005). Control of Manufacturing Systems with a Two-value, Production-Dependent Failure Rate. *Automatica*. 41(11), 1943–1948.

Martinelli, F. (2007). Optimality of a Two-threshold Feedback Control for a Manufacturing System with a Production Dependent Failure Rate. *IEEE Transactions on Automatic Control.* 52(10), 1937–1942.

Peng, H., & van Houtum, G. J. (2016). Joint Optimization of Condition-Based Maintenance and Production Lot-Sizing. *European Journal of Operational Research.* 253(1), 94–107.

Salonen, A. (2011). *Strategic Maintenance Development in Manufacturing Industry*. Doctoral Dissertation, School of Innovation, Design and Engineering, Malardalen University, Sweden. *Operations Management*. 4(2) 133–170.

Slaugh, V. W., Biller, B. & S. R. Tayur. (2016). Managing Rentals with Usage-Based Loss. *Manufacturing & Service Operations Management*. 18(3) 429–444.

Zhang, X. & Zeng, J. (2017). Joint Optimization of Condition-Based Opportunistic Maintenance and Spare Parts Provisioning Policy in Multiunit Systems. *European Journal of Operational Research.* 262(2) 479–498.

Zied, H., Sofiene, D. & Nidhal, R. (2011). Optimal Integrated Maintenance/Production Policy for Randomly Failing Systems with Variable Failure Rate. *International Journal of Production Research.* 49(19) 5695–5712.