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Effects of Maintenance Grouping Strategy on Critical Equipment Availability in Petrochemical Industry

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Abstract— The main purpose of the research is to develop a mathematical model that would aid the prediction of critical equipment failure period, determine the maintenance probability as well as analyze maintenance cost under different operating conditions and maintenance grouping strategy so that the most cost-effective grouping strategy is obtained. In the study, equipment failure probability was utilized in determining maintenance cost under different maintenance grouping strategies (dynamic, opportunistic and static maintenance grouping strategies). Condition monitored data of the critical equipment (a single-stage centrifugal compressor) components was collected at Warri Refinery and Petrochemical Company, Ekpan-Warri, Nigeria. This data was used to validate the developed model. The result shows that the maintenance cost is affected by both equipment speed condition and the maintenance grouping strategy adopted. It was generally observed that the failure probabilities for static and dynamic maintenance grouping strategies are very low, which implies that there is low maintenance severity and consequent reduction in maintenance backlog. Maintenance set-up cost can substantially be saved when maintenance activities on different components are executed simultaneously, (maintenance grouping). Since execution of a group of maintenance activities requires single set-up, maintenance practitioners can use the knowledge of optimal maintenance grouping strategy to effectively schedule maintenance activities and thus reduce maintenance cost significantly. The outcomes have led to optimal decision making on the economic selection of appropriate maintenance grouping strategy.

Index Terms— Critical equipment, failure probability, maintenance grouping strategy, maintenance cost.

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1 INTRODUCTION

Maintenance is carried out on equipment to extend the lifetime or at least the mean lifetime to the next failure at which repair may be costly. The frequency at which maintenance activities are carried out (maintenance severity) and the undesirable consequences of such on plant's critical equipment can greatly affect the maintenance cost. However, this can be reduced by adopting a cost-effective maintenance grouping strategy and proper maintenance scheduling.

Industrial plants have always employed maintenance programmes to keep their equipment in good working condition for as long as feasible. These programmes have hitherto been traditional maintenance approaches which consist mostly of pre-defined activities carried out at regular intervals. However, such a maintenance policy can be quite inefficient and costly if not properly prioritized. Amongst the various alternative maintenance grouping strategies available, a comparison can be made based on information obtained through periodic or continuous monitoring of equipment health and an optimal grouping strategy can be selected using maintenance cost analysis.

In an organization, such as the petrochemical plant, where production operations are automated and complex machineries are utilized, maintenance cost can significantly be minimized when maintenance activities on different components are executed simultaneously, (maintenance grouping). In this study, a mathematical model was developed to aid the prediction of equipment failure period, determine maintenance probability and severity as well as analyze maintenance cost under different operating conditions and maintenance grouping strategy so that the most cost-effective grouping strategy is identified.

2 OVERVIEW OF CONDITION BASED MAINTENANCE

Bengtsson [1] defined condition based maintenance (CBM) as "predictive maintenance based on performance and/or parameter monitoring and the subsequent actions." The performance and parameter monitoring may be scheduled, or continuous. In a more recent study, Veldman et al. [2], defined CBM as the use of monitoring techniques to diagnose or predict failure of a physical artifact, and the activities needed to restore this artifact into its intended condition. CBM is thus a maintenance technology that utilizes condition monitoring tools to analyze the current condition of the item and, through that knowledge, set up proper preventive maintenance schedules.

Condition based maintenance model is one of the most recent advancement being introduced into maintenance planning and control [3-5]. The CBM models have improved tremendously the effectiveness in planning and control of maintenance of industrial machineries, in the areas of cost and time savings in automobile, power, energy, and manufacturing industries [6-9]. CBM models assume that all equipment will deteriorate and that partial or complete loss of function will occur. It relies on the fact that majority of failures do not occur instantaneously but develop over a period of time. CBM

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is carried out each time the value of a given system parameter exceeds a predetermined value. It uses various process parameters such as pressure, temperature, vibration, and flow and material samples such as oil and air whose conditions are being monitored. With these parameters and samples, condition based measured data obtained indicates the system or equipment health, performance, integrity (strength) and provides information for planning timely for predictive or proactive maintenance action on such system or equipment.

Once the timing of equipment failure is known, action can be taken to prevent (predictive) or delay failure (proactive). The goal of condition based maintenance is to optimize equipment reliability and availability by determining the need for maintenance activities based on equipment condition. Using predictive techniques, condition monitoring and observations can be used for projecting the most probable time of failure. This enhances the performance of predictive techniques on the plant with plans and actions in a proactive manner. CBM allows the lowest cost and most effective maintenance programme by determining the correct activity at the correct time.

2.1 Maintenance Optimization Models

The overall objective of maintenance optimization models is to determine the frequency and/or timing of preventive and/or corrective maintenance activities, in order to arrive at an optimal balance between the costs and benefits of both. Maintenance optimization models are categorized as mathematical models for single unit systems and mathematical models for multiple unit systems [10].

In general, the philosophy of most maintenance optimization models for single unit systems is to decide at each feasible moment whether it is cost-effective to carry out preventive maintenance now, or postpone it to the next feasible moment [11,12]. The main differences between these models originate from their interpretation of the mechanism with which preventive maintenance is, or can be, activated. In this respect, a clear distinction is made between continuous review models, periodic review models and opportunistic review models.

According to Niebel [13], continuous review models are usually of a predictive, condition-based nature and the assumption in this model is that the condition of the system can be monitored continuously. It involves continuous monitoring of those parameters that allow the accurate prediction of failure so as to permit precise scheduling of repairs without the costs of emergency downtime. Mathematical models in this area derived their values from finding the parameters and corresponding threshold values, with which the occurrence of failures can be predicted accurately.

Unlike continuous review models, in periodic review models, it is assumed that the condition of the system cannot be monitored continuously, as is the case in continuous review models, but only through periodic inspection at fixed costs. Inspections are usually carried out at regular intervals, and are either time-based or use-based. Typical maintenance models of the use-based type are the age replacement and minimal repair models [14]. While classical examples of time-based maintenance models are the block replacement model [15], the standard inspection model [16] and the delay time model [17]. Mathematical models in this area are usually concerned with finding the optimal maintenance interval, either time-based or use-based, in order to arrive at an optimal balance between the costs and benefits of preventive and corrective maintenance.

Opportunistic review models assumes that inspections cannot be carried out at any time, as is the case in periodic review models, but only at so-called maintenance opportunities. The underlying observation behind these models is that in many practical situations, preventive maintenance on non-critical units is delayed to some moment in time where the unit is not required for production [11]. Generally, such opportunities may arise due to random breakdowns and/or withdrawn production orders. Mathematical models in this area are primarily used to determine whether a maintenance activity must be conducted at a given opportunity or it must be postponed to the next one [18,19].

Most maintenance optimization models for multiple unit systems that have the potential of reductions in set-up costs and/or times can be justified if maintenance activities are carried out simultaneously (maintenance grouping). Mathematical models in this area are categorized into [10]:

1. Static grouping strategy (long- term);
2. Dynamic grouping strategy, (medium-term); and
3. Opportunistic grouping strategy (short-term)

Although each grouping strategy takes place at a different planning level, their mutual objective is to improve maintenance efficiency in terms of reducing set-up times and costs in an operational planning phase.

Static grouping refers to the combination of planned preventive maintenance activities in a strategically planning phase. These models are classified as direct and indirect grouping models. In direct grouping models, the collection of preventive maintenance activities is partitioned into several maintenance packages, each of which is executed at an interval that is optimal for that package. In indirect grouping models maintenance packages are not determined in advance, but are formed indirectly whenever the maintenance of different units coincides. Several research studies have been done on static grouping models [20-22]. However, static grouping models basically attempt to find the optimal balance between the costs of deviating from the optimal preventive maintenance intervals for individual units, and the benefits of combining preventive maintenance activities on different units.

Dynamic grouping refers to the combination of planned preventive maintenance activities with each other, and/or with plannable corrective maintenance activities in a tactical planning phase. Plannable corrective maintenance is only possible if the repair of failed units can be postponed to a more suitable moment in time, possibly because standby units are available, or the unit does not affect the system as a whole. The main difficulty of dynamic grouping models is that the failure of a unit cannot be predicted in advance. Therefore, dynamic grouping models make use of a finite horizon in order to arrive at a sequence of decisions.

Wildeman, et al. [23,24] investigated how short-term circumstances can influence the planning and how important it is to take this into account. They compared the costs of following a static grouping method with the costs according to an approach which can adapt this long-term plan to dynamically changing information (such as a variable use of components and the occurrence of maintenance opportunities). They showed how the long-term approach was used as a basis for the dynamic approach, and hence how the long-term plan was adapted to deal with dynamic influences. However, Mathematical models for dynamic grouping derive their value from finding an optimal balance between the costs of postponing corrective maintenance activities, and the benefits of combining them with other preventive and/or corrective maintenance activities.

Opportunistic grouping refers to the combination of planned maintenance activities with unplanned maintenance activities in an operational planning phase. In these models, the failure of a particular unit is used as an opportunity for planned maintenance on other units. The opportunistic maintenance grouping is difficult to manage in practice, since it affects the plannable nature of preventive maintenance. Nevertheless, if all the preparations needed for preventive maintenance have been made in advance, it is an effective method to reduce set-up costs and times in an operational planning phase. Many research works have been carried out on opportunistic maintenance grouping models [25-29]. However, mathematical models for opportunistic maintenance grouping attempt to find an optimal balance between the costs of advancing planned maintenance activities, and the benefits of combining them, with other unplanned maintenance activities.

2.2 Maintenance Strategy Selection Problem

Maintenance strategy selection is a strategic decision making problem that has become a major challenge to contend with in the manufacturing industry [30]. Several research studies have been presented on the Maintenance Strategy Selection Problem (MSSP). Mechefske and Wang [31] used fuzzy linguistic approach for the Multi Criteria Decision Making. In his approach, the organization first select its goals and then by interviewing managers, employs the importance of each goal and the capability of each maintenance strategy to satisfy each goal that is captured. Thereafter, some equations in the fuzzy environment are then used to select the optimum maintenance strategy. This approach however did not consider the variety of opinion but limit the opinions to deterministic linguistic variables

In another study, Al-Nayar and Alsyouf [32] were of the view that the most efficient maintenance approach is the one that is able to provide and utilize the required information about the changes in the equipment/machine failure causes behaviour. In their work, they used past data and technical analysis of process machines and components to identify the criteria for Multi Criteria Decision Making (MCDM) problem. They employed fuzzy inference system to assess the capability of each maintenance approach and finally utilized Simple Additive Weighting (SAW) to select the most efficient maintenance approach.

The paper by Ivy and Nembhard [33] presents the integration of statistical quality control and partially observable Markov decision processes for the evaluation of maintenance policies under conditions of limited information. Sharma and Bahadoorsingh [34] propose an approach based on fuzzy linguistic modeling to select the most effective maintenance strategy for the components/parts associated with a system. In another work, Bertolini and Bevilacqua [35] develop a combined Analytic Hierarchy Process (AHP) - Goal Programming (GP) model for maintenance selection policy problem and used it in a case study for identifying the optimal maintenance policy for a set of centrifugal pumps operating in the process and service plants of an oil refinery.

In decision making process, accurate estimation of pertinent data relevant to the problem is a crucial step. However, the Maintenance Strategy Selection Problem which is a Multi Criteria Decision Making problem faces the problem in estimating related factors. A landmark in solving this problem was achieved by Wang et al. [36]. In their work, they used triangular fuzzy number in fuzzy Analytic Hierarchy Process to model the uncertainty in the selection process.

Another notable contribution in this research area is the study by Azizollah et al. [37] who propose a new approach to the Maintenance Strategy Selection Problem which can determine the best maintenance strategy by considering the uncertainty level and also all the varieties in maintenance criteria and their importance. They used Fuzzy Delphi method in Simple Additive Weighting (SAW) shown in a heuristic algorithm for the estimation of the importance of goals and the capability of each maintenance strategy to satisfy each maintenance goals with Fuzzy numbers. This method allows both tangible and intangible goals in dealing with the selection problem and generates an L–R Fuzzy number that measures information about the nature of opinions more adequately.

More recently, significant studies have been carried out on maintenance strategy selection problem by integrating different methods such as equal deterioration theory, analytical hierarchy process, goal programming, genetic algorithm, fuzzy multi criteria mathematical models among others to address this problem [38-44]. However, in many of these studies, variation in component operational condition was not considered and machine deterioration which is actually stochastic is assumed to be linear for ease of modeling. Moreover, maintenance set-up cost which can significantly be minimized when maintenance activities on different components are executed simultaneously, (maintenance grouping) was not taken into cognizance in these studies. Since execution of a group of maintenance activities requires single set-up, maintenance grouping strategy could significantly reduce maintenance cost. This study provides a probabilistic approach for maintenance scheduling that reflects the nature of uncertainty in the maintenance environment and also presents a framework for optimal decision making on the economic selection of appropriate maintenance grouping strategy.

3 DEVELOPMENT OF MODEL

A model based on equipment condition has been developed for predicting equipment failure period under progressive deterioration. Condition-based parameters associated with critical equipment maintenance include vibration, temperature, oil pressure, periodic deterioration, and failure pattern. Measurement of the indicator's variables such as temperature, vibration and pressure were taken and recorded at the beginning of the period for the single unit every T time units. Time between inspections was set at weekly basis and made constant. Failures were realistically, expected to occur at any time in any inspection period, and maintenance maybe carried out instantaneously or progressively.

3.1 Instantaneous Maintenance

For instantaneous condition maintenance case, a condition based model based on periodic inspection was formulated as follows [45]:

$$V_i^{t_a} = \max\,(V_{ij})_k \tag{1}$$

Where,
j = number of coordinates vibrations measured on the equipment/components i of function k at inspection period t_a.

$$T_i^{t_a} = \max\,(T_{ij})_k \tag{2}$$

Where,
j = number of coordinates temperatures measured on the equipment/components I of function k at inspection period t_a.

$$P_i^{t_a} = \max\,(P_{ij})_k \tag{3}$$

Where,
j = number of coordinates oil pressures measured on the equipment/components i of function k at inspection period t_a.

$$\text{If}\ \left\langle \begin{array}{l} V_i^{t_a} \geq V_c^{t_a}, \text{maintain i, otherwise do not} \\ T_i^{t_a} \geq T_c^{t_a}, \text{maintain i, otherwise do not} \\ P_i^{t_a} \geq P_c^{t_a}, \text{maintain i, otherwise do not} \end{array} \right.$$

Where,
$V_c^{t_a}$, $T_c^{t_a}$ and $P_c^{t_a}$ are critical values of vibration, temperature and pressure respectively. At or beyond these critical values, the failure of mechanical components i is anticipated.

3.2 Instantaneous Maintenance Cost Implication

The maintenance cost, $C_m^{t_a}$ at the end of inspection period, t_a incurred on equipment /components due for maintenance at this period, t_a is given as [45]:

$$C_m^{t_a} = C_p + \sum_{r=1}^{z} C_r^{t_a} M_r^{t_a} \tag{4}$$

Where,
C_p is maintenance set up cost, and
C_r is the cost of maintenance of equipment/component of identity r at the end of inspection period t_a.

Cost of maintenance, $C_r^{t_a}$ comprises of the costs of maintenance personnel, tools/equipment, utilities and other miscellaneous cost elements including downtime cost, waiting cost and hiring/standby if (extra) tools/equipment are required.

Thus, $C_r^{t_a}$ is obtained from,

$$C_r^{t_a} = \left(C_q + C_e + C_u + C_s\right)_r^{t_a} \tag{5}$$

3.3 Progressive Deterioration Measurement

The above instantaneous model of condition based maintenance; based on periodic inspection is deficient because failure in some cases might have occurred before the next inspection period [28]. Therefore, a dynamic model is necessary to monitor the progressive deterioration in equipment/components so that preventive/corrective maintenance action is planned before the actual failure. The model extends to consider the operating conditions such as vibration (V), temperature (T), and pressure (P). Practically several inspection tests are to be carried out at different operating conditions at regular intervals from which deterioration (growth) factor (for failure monitoring conditions such as V, T and P) is established (from the experimental data generated) using rule of thumb [30,45]

If the value of vibration, $V_i^{t_a}$ at the point of installation of equipment/component i is denoted by $V_i^{t_0}$, then the next inspection period $V_i^{t_a}$, with a = 1, is given as:

$$V_i^{t_1} = V_i^{t_0} + u_v V_i^{t_0} = V_i^{t_0}\left(1 + u_v\right) \tag{6}$$

Where,
u_v is the periodic deterioration growth factor for vibration measurement.
Similarly, with a = 2,

$$V_i^{t_2} = V_i^{t_1} + u_v V_i^{t_1} = V_i^{t_1}\left(1 + u_v\right) \tag{7}$$

$$= V_i^{t_0}\left(1 + u_v\right)^2 \tag{8}$$

Thus, generally,

$$V_i^{t_a} = V_i^{t_0}\left(1 + u_v\right)_k^a \tag{9}$$

The value of $V_i^{t_a}$ is best obtained from the manufacturer of the equipment/component [45].

$$u_v = \left(\frac{V_i^{t_1} - V_i^{t_0}}{V_c^{t}}\right)_b, \quad V_i^{t_1} = \max\left(V_{ij}\right)_k \tag{10}$$

Where,
$V_i^{t_1}$ is the vibration value first witnessed in period t_1 and maximum value chosen as done in early determination. Normal vibration value $V_i^{t_0}$ is the vibration when the equipment/component is new and the manufacturer of such equipment/components supplied this value in their manufacturer performance test records. The value, $V_c^{t_a}$ represent the critical vibration value which shows that failure is imminent. Many manufacturers of equipment also supplied this value to their customers.
The subscript b denotes the test condition of estimating $V_i^{t_1}$, e.g. speed.

Similar conditions stated above hold for temperature $T_i^{t_a}$ and pressure $P_i^{t_a}$ measurements. These are stated respectively as:

$$T_i^{t_a} = T_i^{t_0}\left(1+u_T\right)_k^a \tag{11}$$

$$P_i^{t_a} = P_i^{t_0}\left(1+u_P\right)_k^a \tag{12}$$

And their corresponding u_T and u_P are respectively:

$$u_T = \left(\frac{T_i^{t_1} - T_i^{t_0}}{T_c^t}\right)_b, \; T_i^{t_1} = \max\left(T_{ij}\right)_k \tag{13}$$

$$u_P = \left(\frac{P_i^{t_1} - P_i^{t_0}}{P_c^t}\right)_b, \; P_i^{t_1} = \max\left(P_{ij}\right)_k \tag{14}$$

The quantities $T_i^{t_1}, T_i^{t_0}, T_c^{t_a}, P_i^{t_1}, P_i^{t_0}, P_c^{t_a}, u_T, u_P$ are obtained similar to that of vibration described above.

Maintenance period is determined using measurement similar to that of instantaneous maintenance conditions aforementioned (Kareem and Jewo, 2011), that is:

$$\text{If} \left\langle \begin{array}{l} V_i^{t_a} \geq V_c^{t_a}, \text{maintain i, otherwise do not} \\ T_i^{t_a} \geq T_c^{t_a}, \text{maintain i, otherwise do not} \\ P_i^{t_a} \geq P_c^{t_a}, \text{maintain i, otherwise do not} \end{array} \right.$$

Maintenance actions carried out after the failure warning periods are assumed to be capable of restoring defective equipment/components back to their original (new) condition. Many models on condition based monitoring neglected downtime effect in the system which may be significant in some cases (Tajadod et al 2011). The effect of this downtime, may be neutralized with the installation of standby facility, if, economically viable, or wait until after maintenance action is carried out on the primary equipment. Also, equipment/component failure is not a deterministic affair but probabilistic. This is very important in determining maintenance cost and determining groupings (opportunistic, dynamic, and static) of maintenance actions. Under the exponential distribution arrangement, the reliability, $R(t)_j^i$ of component/equipment, i in the plant, j at time, t without a standby is given as (Kareem and Jewo, 2011);

$$R(t)_j^i = e^{-\lambda_i t} \tag{15}$$

While the corresponding probability of failure of component/equipment, i in plant, j is obtained from relation:

$$P(t)_j^i = 1 - e^{-\lambda_i t} \tag{16}$$

Similarly, the reliability of equipment/components with a single (passive) standby at scheduled period, t is presented in Equation (18) as:

$$R(t) = e^{-\lambda t} + e^{-\lambda t}(\lambda t) \tag{17}$$

And corresponding probability of failure at time, t, P (t) is presented in Equation (3.3b) as:

$$P(t) = 1 - \left(e^{-\lambda t} + e^{-\lambda t}(\lambda t)\right)$$

Where, λ is being estimated from,

$$\lambda = \frac{\sum_{r=1}^{z} M_r^{t_a}}{T_i^{t_a}} \tag{18}$$

Where, r = 1,2,3…z
For dynamic policy, r = 1
For static policy, r = z, and
For opportunistic policy, 1<r<z
Failure rate, (λ) is obtained based on maintenance policy adopted, opportunistic, dynamic, or static after implementing the iterable equation, (18).

3.4 Progressive Maintenance Cost Implication

From the previous equations for instantaneous system, total maintenance cost $C_m^{t_a}$ for opportunistic and static/long-term maintenance policy is given as:

$$C_m^{t_a} = P(t)\left[C_p + \sum_{r=1}^{z} C_r^{t_a} M_r^{t_a}\right] \tag{19}$$

The following relation gives the cost estimate for progressive or dynamic maintenance policy.

$$C_m^{t_a} = \sum_{\psi=1}^{\gamma} P(t)\left[C_{p\psi} + \sum_{r=1}^{z} C_r^{t_a} M_r^{t_a}\right] \tag{20}$$

$\psi = 1,2,\ldots,\gamma,$ is the failure recorded in period t.
P (t) is the probability of such failure(s)
$C_{p\psi}$ is the set-up cost of maintaining the failures
$C_r^{t_a}$ and $M_r^{t_a}$ are as obtained before.
The developed models were validated using data collected from a petrochemical plant located in Ekpan-Warri, Nigeria.

TABLE 2
GEAR COMPONENTS/COMPUTED DETERIORATION GROWTH FACTOR AND EXPECTED FAILURE TIME

Gear Housing Temperature	*Speed bi,,i =1,2...,3*		*TO (OC)*	*T1 (OC)*	*TC (OC)*	*UT*	*Expected failure time (Weeks)*	*Corresponding failure Temp. (oC)*	
								Min	Max
	b1	2984	64	88	105	0.228	3	96.51	118.52
	b2	2989	65	88	105	0.219	3	96.59	117.74
	b3	2993	64	88	105	0.228	3	96.51	118.52
Gear bearing Temperature	Speed bi ,i =1,2...,3		TO (OC)	T1 (OC)	TC (OC)	UT	Expected failure time (Weeks)	Corresponding failure Temp. (oC)	
								Min	Max
	b1	2984	48	60	90	0.133	6	89.62	101.54
	b2	2989	48	60	90	0.133	6	89.62	101.54
	b3	2993	48	61	90	0.144	6	94.05	105.59
Gear Housing Vibration Amplitudes	Speed bi, i =1,2...,3		VO (mm/s)	V1 (mm/s)	VC (mm/s)	UV	Expected failure time (Weeks)	Corresponding failure Amplitudes. (mm/s)	

4 MODEL VALIDATION

Condition monitored data of a single-stage centrifugal compressor components including electric motor, gear and blower was collected at Warri Refinery and Petrochemical plant, Ekpan-Warri, Nigeria [46]. This data was used to validate the developed model. The data collected on the aforementioned components was analyzed using the relations for deterioration growth factor, failure periods, maintenance probability and maintenance cost respectively. Tables 1, 2 and 3 show data for electric motor components, gear components and blower components, with their computed deterioration growth factor, expected failure time, and corresponding failure temperatures and amplitudes respectively.

TABLE 3
BLOWER COMPONENTS/COMPUTED DETERIORATION

Blower Casing Temperature	*Speed bi,i =1,2...,3*		*TO (OC)*	*T1 (OC)*	*TC (OC)*	*UT*	*Expected failure time (Weeks)*	*Corresponding failure Temp. (oC)*	
								Min	Max
	b1	2984	63	78	200	0.075	16	186.41	200.39
	b2	2989	65	78	200	0.065	18	189.61	201.93
	b3	2993	63	78	200	0.075	16	186.41	200.39
Blower Bearing Temperature	Speed bi,i =1,2...,3		TO (OC)	T1 (OC)	TC (OC)	UT	Expected failure time (Weeks)	Corresponding failure Temp. (oC)	
								Min	Max
	b1	2984	25	27	77	0.0259	44	75.07	77.010
	b2	2989	25	27	77	0.0259	44	75.07	77.010
	b3	2993	25	27	77	0.0259	44	75.07	77.010
Blower Casing Vibration Amplitudes	Speed bi,i =1,2...,3		VO (mm/s)	V1 (mm/s)	VC (mm/s)	UV	Expected failure time (Weeks)	Corresponding failure Amplitudes. (mm/s)	
								Min	Max
	b1	2984	0.2	0.4	8	0.025	150	7.923	8.121
	b2	2989	0.2	0.4	8	0.025	150	7.923	8.121

5 RESULTS AND DISCUSSION

The expected failure period under various operating speed conditions for the critical equipment and maintenance policy was used to determine the failure probability and maintenance cost of the components/equipment and the computed results are tabulated in Tables 4, 5, 6, and 7 respectively.

In these Tables, failure probability varies, depending on the component and maintenance policy under consideration. It can be observed in Table 4 that the blower component has the lowest probability of failure under all maintenance policies, irrespective of the speed condition, while the gear component has the highest probability of failure. Similarly, Tables 5, 6, and 7 follow the same trend, with blower component having

TABLE 4
CRITICAL EQUIPMENT COMPONENTS FAILURE PROBABILITY FOR 1ST QUARTER

Condition of operation Speed (rpm), b_i, i =1,2,3	*Maint. policy*	*Electric Motor Components*		*Gear Components*			*Blower Components*	
		Winding (Pt)	Bearing (Pt)	Gear (Pt)	Gear Bearing (Pt)	Gear Housing (Pt)	Blower (Pt)	Blower Bearing (Pt)
b_1	Dynamic	0.2209	0.9257	0.9869	0.8853	0.2661	0.5563	0.2555
2984	Opportu-nistic	0.9945		0.9999				0.9126
	Static	0.3935		0.6047				0.2289
b_2	Dynamic	0.2604	0.7275	0.9869	0.8853	0.2661	0.5140	0.2555
2989	Opportu-nistic	0.9257		0.9999				0.8854
	Static	0.4537		0.6047				0.2289
b_3	Dynamic	0.4953	0.7275	0.9869	0.8854	0.2661	0.5563	0.2555
2993	Opportu-nistic	0.9253		0.9999				0.9126
	Static	0.7453		0.6047				0.2289

TABLE 1
ELECTRIC MOTOR COMONENTS AND ITS GROWTH DETERIORATING FACTOR

Electric Motor Winding Temperature	*Speed bi, i. =1,2...,3*		*TO (OC)*	*T1 (OC)*	*TC (OC)*	*UT*	*Expected failure time (Weeks)*	*Corresponding failure Temp. (oC)*	
								Min	Max
	b1	2984	58	61	155	0.0194	52	154.53	157.53
	b2	2989	68	71	155	0.0194	43	152.40	155.36
	b3	2993	60	68	155	0.0194	46	154.32	157.32
Electric Motor Bearing Temperature	Speed bi, i. =1,2...,3		TO (OC)	T1 (OC)	TC (OC)	UT	Expected failure time (Weeks)	Corresponding failure Temp. (oC)	
								Min	Max
	b1	2984	60	64	77	0.0519	5	73.46	77.27
	b2	2989	60	62	77	0.0259	10	75.53	77.48
	b3	2993	60	62	77	0.0259	10	75.53	77.48

TABLE 5
CRITICAL EQUIPMENT COMPONENTS FAILURE PROPABILITY FOR 2ND QUARTER

Speed (rpm), b_i, i = 1,2,3	*Maint. policy*	*Electric Motor Components*		*Gear Components*			*Blower Components*		
		Winding (Pt)	Bearing (Pt)	Gear (Pt)	Gear Bearing (Pt)	Gear Housing (Pt)	Blower (Pt)	Blower Bearing (Pt)	Blower Casing (Pt)
b_1 2984	Dynamic	0.3935	0.9945	0.9998	0.9869	0.4614	0.8031	0.4458	0.1590
	Opportunistic	0.99997		1			0.9924		
	Static	0.6321		0.8438			0.4055		
b_2 2989	Dynamic	0.4529	0.9257	0.9998	0.9869	0.4614	0.7638	0.4458	0.1577
	Opportunistic	0.9945		1			0.3515		
	Static	0.7015		0.8438			0.4055		
b_3 2993	Dynamic	0.7453	0.9257	0.9998	0.9869	0.4614	0.8031	0.4458	0.1589
	Opportunistic	0.9945		1			0.9924		
	Static	0.9351		0.8438			0.4055		

the lowest probability of failure under all maintenance policies irrespective of the speed condition, while the gear components have the highest probability of failure. However, the lowest probability of failure is observed in the first quarter of the year, while the highest probability of failure is either in the second or third quarter of the year.

5.1 Quarterly Maintenance Cost for the Critical Equipment

The total maintenance cost for the whole critical equipment was calculated based on maintenance set-up cost (C_p) and maintenance repair cost, (C_r). The maintenance set up cost is the cost of deploying tools/equipment, maintenance personnel and other ancillary facilities needed for maintenance. While maintenance repairs cost is the cost of carrying out maintenance on critical equipment components per breakdown, (that is, cost of labour and tools/equipment required for maintenance). These are presented in Tables 8 and 9 respectively. The quarterly maintenance cost per component for dynamic, opportunistic and static maintenance policies under various speed conditions as determined using Equations 19 and 20, and C_p and C_r values presented in Tables 8 and 9 were summed up to obtain the total maintenance cost for the critical equipment. Table 10 shows the quarterly maintenance cost for the critical equipment.

Determined failure probabilities, set-up and repair costs obtained were used for the computations. The values obtained from these computations were used to plot graphs, which actually describe the maintenance cost trends at various speed conditions and maintenance policies.

TABLE 6
CRITCAL EQUIPMENT COMPONENTS FAILURE PROBABILITY FOR 3^{RD} QUARTER

Condition of operation Speed (rpm), bi, i = 1,2,3	*Maint. policy*	*Electric Motor Components*		*Gear Components*			*Blower Components*		
		Winding (Pt)	Bearing (Pt)	Gear (Pt)	Gear Bearing (Pt)	Gear Housing (Pt)	Blower (Pt)	Blower Bearing (Pt)	Blower Casing (Pt)
b1 2984	Dynamic	0.3935	0.9945	0.9998	0.9869	0.4614	0.8031	0.4458	0.1590
	Opportunistic	0.99997		1			0.9924		
	Static	0.6321		0.8438			0.4055		
b2 2989	Dynamic	0.4529	0.9257	0.9998	0.9869	0.4614	0.7638	0.4458	0.1577
	Opportunistic	0.9945		1			0.3515		
	Static	0.7015		0.8438			0.4055		
b3 2993	Dynamic	0.7453	0.9257	0.9998	0.9869	0.4614	0.8031	0.4458	0.1589
	Opportu-	0.9945		1			0.9924		

Figures 1, 2, and 3 present the plot of quarterly total maintenance cost for whole critical equipment at various maintenance policies. For dynamic and static maintenance policies, minimum maintenance cost was obtained in first quarter when the equipment is operated at speed conditions 2989rpm and 2984rpm respectively. Similarly, the cost trend also shows

TABLE 7
CRITICAQL EQUIPMENT COMPONENTS FAILURE PROBABILITY FOR THE FOUTH QUARTER

Condition of operation Speed (rpm), bi, i = 1,2,3	*Maint. policy*	*Electric Motor Components*		*Gear Components*			*Blower Components*	
		Winding (Pt)	Bearing (Pt)	Gear (Pt)	Gear Bearing (Pt)	Gear Housing (Pt)	Blower (Pt)	Blower Bearing (Pt)
b1 2984	Dynamic	0.6315	0.9999	0.9999	0.9998	0.7099	0.9612	0.6928
	Opportunistic	0.9999		1				0.9999
	Static	0.8647		0.9756				0.6465
b2 2989	Dynamic	0.7007	0.9945	0.9999	0.9998	0.3509	0.9442	0.6928
	Opportunistic	0.9999		1				0.9998
	Static	0.9109		0.9756				0.6465
b3 2993	Dynamic	0.9351	0.9945	0.9999	0.9998	0.7099	0.9612	0.6928
	Opportunistic	0.9999		1				0.9999
	Static	0.9958		0.9756				0.6465

that it is best to schedule maintenance in the second quarter with the adoption of opportunistic maintenance policy, while the equipment is run at speed condition 2998 rpm. For third quarter scheduling, dynamic maintenance policy is economical with the equipment operated at speed condition 2884rpm

TABLE 8
MAINTENANCE SET-UP COST OF CRITICAL EQUIPMENT COMPONENTS PER BREAKDOWN

Condition of operation Speed (rpm), bi, i = 1,2,3		Electric Motor Components		Gear Components			Blower Components		
		Winding	Bearing	Gear	Gear Bearing	Gear Housing	Blower	Blower Bearing	Blower Casing
b1	2984	Cp (□)	Cp (□)	Cp(□)	Cp (□)	Cp (□)	Cp (□)	Cp (□)	Cp (□)
		187500	187500	187500	187500	187500	187500	187500	187500
b2	2989	Cp (□)	Cp (□)	Cp(□)	Cp (□)	Cp (□)	Cp (□)	Cp (□)	Cp (□)
		187500	187500	187500	187500	187500	187500	187500	187500
b3	2993	Cp (□)	Cp (□)	Cp(□)	Cp (□)	Cp (□)	Cp (□)	Cp (□)	Cp (□)
		187500	187500	187500	187500	187500	187500	187500	187500

TABLE 10
TOTAL MAINTENANCE COST FOR THE WHOLE CRITICAL EQUIPMENT

Condition of operation Speed (rpm), bi i = 1,2,3		Maintenance policy	Quarter 1 (13 Weeks) (□)	Quarter 2 (26 Weeks) (□)	Quarter 3 (39 Weeks) (□)	Quarter 4 (52 Weeks) (□)
b1	2984	Dynamic	1,388,459.92	1,737,521.38	1,938,719.43	2,079,102.69
		Opportunistic	1,651,956.30	1,702,684.09	1,706,828.92	1,707,189.34
		Static	699,815.17	1,070,233.90	1,281,949.57	1,411,847.20
b2	2989	Dynamic	1,315,581.98	1,718,619.97	1,936,318.00	1,971,507.17
		Opportunistic	1,600,811.34	1,314,963.60	1,706,196.59	1,707,129.27
		Static	730,270.35	1,105,343.36	1,312,303.57	1,435,219.78
b3	2993	Dynamic	1,408,008.05	1,829,462.71	2,045,907.78	2,177,229.01
		Opportunistic	1,616,948.02	1,699,952.23	1,706,677.15	1,707,189.34
		Static	817,320.79	1,223,521.60	1,386,468.51	1,478,170.69

or 2989 rpm. While for opportunistic maintenance policy the equipment could be run at any speed condition. However, it can be observed from the plot trend that for static maintenance policy, there is progressive increase in the maintenance cost up to the last quarter for all speed conditions. Static maintenance policy gives the minimum maintenance cost and the optimum period for maintenance at any speed condition in the first quarter.

TABLE 9
CALCULATED VARIABLE MAINTENANCE COST

Condition of operation Speed (rpm), bi i = 1,2, 3		Electric Motor Components		Gear Components			Blower Components		
		Winding	Bearing	Gear	Gear Bearing	Gear Housing	Blower	Blower Bearing	Blower Casing
b1	2984	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)
		144600	173800	152600	108000	152600	152600	108000	152600
b2	2989	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)
		144600	173800	152600	108000	152600	152600	108000	152600
b3	2993	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)	Cr (□)
		144600	173800	152600	108000	152600	152600	108000	152600

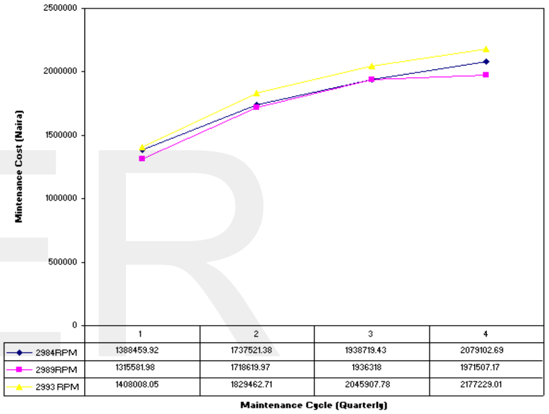

Fig. 1. Dynamic Policy Maintenance Cost for the Whole Critical Equipment

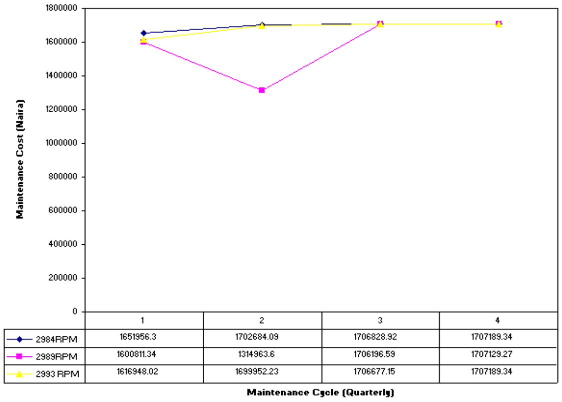

Fig. 2. Opportunistic Policy Total Maintenance Cost for the Whole Critical Equipment

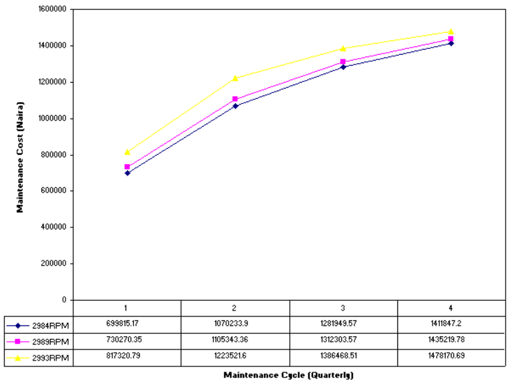

Fig. 3. Static Policy Total Maintenance Cost for the Whole Critical Equipment

6 CONCLUSION

The study carried out using data collected from Warri Refinery and Petrochemical Company, Ekpan-Warri, Nigeria shows that for the critical equipment, the maintenance cost is affected by both equipment speed condition and maintenance policy adopted. It was generally observed from the plot trends that the failure probability for static maintenance policy is very low, which implies that there is low maintenance severity and consequent reduction in maintenance backlog for the various units of the equipment. Similarly, the failure probability for dynamic maintenance policy is quite low, implying that there is also less congestion of maintenance jobs. However, failure probability for opportunistic maintenance policy turned out to be quite high; this invariably would result in congestion of maintenance works on equipment.

Static maintenance policy turned out to be the optimal policy, with cumulative increase per quarter. The worst scenario is opportunistic maintenance policy because of its high failure probability and consequent high maintenance severity. Thus, static maintenance policy is most economical for quarterly maintenance scheduling with the presence of standby equipment. However, dynamic or opportunistic maintenance policy maybe adopted at appropriate operating speed condition, if the standby equipment is unreliable.

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