**Int. j. adv. multidisc. res. stud.** 2022; 2(3):249-258

**Received:** 11-04-2022
**Accepted:** 21-05-2022

International Journal of Advanced Multidisciplinary Research and Studies

**ISSN: 2583-049X**

# A study and analysis of Reliability Centered Maintenance (RCM) in the Energy Industry

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## Abstract

This study presents the Reliability Centered Maintenance (RCM) in the energy industry; with the concept of reliability analysis carried out a real-life study of five (5) key components of a functional Gas Turbine (GT) located in Afam Power PLC in the South-South region of Nigeria. The study applies the reliability centered maintenance planning technique using computational methods to plan the maintenance schedule of the gas turbine plant. First, a maintenance cost function that reflects the present maintenance and operation conditions of the system's components was derived. Second, an estimation of maintenance of the components of the GT using evolutionary algorithm (EA) was carried out, of which the desired subsystem reliability was determined, and maintenance reliability allocated. Third, a reliability growth analysis was used to derive the reliability indices. Two (2) optimization procedures were executed to ascertain the optimum reliability. The results showed that 16.2% maintenance cost was saved when the 2 optimization procedures were compared. A significant correlation between conflicting objectives was achieved by using these optimization procedures thereby converting them to a single optimization model.

**Keywords:** Reliability Centered Maintenance (RCM), Maintenance, Gas Turbine (GT), Evolutionary Algorithm (EA), Run-to-Failure (RTF), Condition Maintenance (CM), Power Industry, Optimization

## 1. Introduction

Global demand for energy is increasing daily and has driven the need for the energy industry to put up measures aimed at sustainably improving the power generation capacity, putting into consideration the factors of cost and safety. Maintenance cost more frequently consumes roughly 60% of the total operational costs Bea *et al*. (2009) [6], and thus it is therefore vital to develop a system that is sustaining, and economically viable. Maintenance is very crucial to the survival of any facility; therefore, any effective maintenance strategy must start its implementation from the management or administrative level. An efficient approach of maintenance by the organization's management can go do a great deal in transmitting the message of maintenance better than any other approach.

Neil (2006) [28] claimed that RCM first came into reality in the 1960s in airline industries following the overwhelming maintenance cost in the aviation sector. Maintenance cost of airline industries in the 1950s was so alarming and as such attracted special attention. Following this a special committee was formed in 1960 comprising both the organization members of FAA and Airline to investigate Preventive Maintenance effectiveness in the sector. The literature thus viewed RCM as an analytical way of identifying which equipment in a establishment are programmed to be periodically maintained on the grounds of Preventative Maintenance (PM) instead of Run-to-Failure (RTF). Its major aim is to know the correct tasks suitable for the PM of a complex system which will on the long run significantly reduce unreliability and maintenance cost. With reference to this literature, any planned and logical PM task can be noted as RCM even though it's not a management initiative. This is contested by Devaraj and Pradeep (2016) [9], which viewed RCM as a strictly a management initiative. High productivity in any industry needs an increased stage of reliability and the availability of the plant or its parts (Fore and Msipha, 2010) [14]. Maintenance and RCM are interconnected (Adoghe *et al*, 2012; Fredrik 2013) [2, 16]. Felecia (2014) [13] therefore defined RCM as a systematic maintenance strategy that is system-reliability based. Marten (2010) [27] highlighted numerous RCM principles including RCM being function oriented, system oriented, reliability centred driven by safety and economics among others. Considering the highlighted dynamism, managers worldwide are sourcing for more updated, better and faster technique to RCM to successfully estimate and adequately apply them (John, 2015) [23]. This is what informed the philosophy of RCM.

In an approach to RCM implementation, Ronald and Lewis (1990) [32] predicted four major steps. The integrated reliability condition maintenance monitoring process centres on continuous improvement all through the equipment life cycle; the main aim of continuous improvement requires CM of lifetime growth, quality and cost of (parts and) equipment all through its lifecycle to attain high reliability (Franciszek, 2015) [15]. Jaehoon *et al*. (2013) [21] proposed a computerized system of managing maintenance activities based on combination of RCM and automated data gathering with the sole aim of supporting the decision making of maintenance managers by the provision of updated reliability assessment of equipment in an automated manner.

The availability status of a complicated system like the GT is majorly linked with reliability of its parts and the adopted maintenance policy (Fermando and Gilberto, 2009) [12]. Maintenance policies do not only affect the component but also its reliability. Fermando and Gilberto (2009) [12] thereby proposed a method (reliability-based concept like the functional-tree development, and the adoption of FMEA) for the evaluation of a gas turbine availabilities and reliability installed in electric power stations. The technique is utilized in identification of some critical parts for enhancement of system's reliability, maintainability and reliability estimation on the bases of previous history of failure record. RCM is also proposed for adoption by the procedure, to enhance the system maintenance standard focused unexpected failure reduction in critical parts. The authors applied the technique in analyzing of two (2) F-series gas turbines each having the capacity of 150MW, installed in a 500MW combined-cycle power plant. The reliability and the availability of these turbines were simulated on the bases of a 5 years failure record. The analysis shows 99% availability for one turbine, and 96% for the other, showing the disparities in their installation and operations. Evolutionary algorithms are class of general-purpose algorithms that can achieve a "remarkable balance between exploration, and exploitation of the search space" (Hamit *et al*., 2004) [19]. They are optimization techniques anchored by natural evolution (John, 2005; 2015) [22, 23].

In real sense, more changes have existed in RCM management development than in any other discipline of management in the past 20 years (Bernd, 2008) [7]. These dynamics are due to the great rise in the variety and size of new physical systems that springs up on daily bases round the world; these systems are usually complex and require programmed maintenance techniques for effective operation and productivity. RCM is reacting to expectation changes (Anandhi *et al*. 2014) [4]. These expectations may comprise of increase in knowledge of the way and manner the failure of equipment affects safety of personnel, assets and the environment, the awareness of the inter-connections between reliability of products and RCM, and the rise in the desire to achieve greater availability of plant availability at lowest possible cost (Ronald and Lewis, 1990) [32]. These changes are challenging the attitudes and expertise of RCM personnel in the industries. RCM personnel comprising of managers and engineers are using an entirely new thinking and acting strategies. Sequel to these changes, Bea *et al*. (2009) [6] therefore introduced an advanced RCM technique of maintenance planning with the instrumentality of the computational approach. Katharina (2011) [24] viewed the idea of RCM as applied to two different models of wind turbine- Vastas V45 600kW & V90-2MW. Ajit *et al*. (2010) [3] proposed the adoption of computer network and practical use of the intelligence agents are applies to industrial facilities, even as e-maintenance has received good attention. Dewangan *et al* (2014) [10] used Bathtub curve to show that failure rate on the bases of system history (of a typical part) always taking a bathtub curve shape. Bathtub curves as generally used in reliability engineering comprises of three parts representing the hazard functions. Katharina (2011) [24] forms the foundations for creating quantitative/ qualitative models for maintenance plan selection and possibly optimization, and only provided limited information on the feedback or outcome of field experience for further upgrading of the wind-turbine design. Felecia (2014) [13] used the fuzzy logic technique to optimize RCM. The technique seeks to remove and eradicate the uncertainty by providing truth in different degrees. Rizauddin and Mohammad (2012) [31] studied RCM in schedule improvement of automobile assembly industry with the sole aim of reducing the checklist maintenance and significantly improve the maintenance practices integrity, focusing on their maintenance functions on the basis of equipment criticality through the adoption of the FMEA.

Sriawat and Kanthapong (2014) [34] adopted the principles of the RCM to improve quality and reliability using a simulation optimization approach based on evolutionary algorithm for PM technique selection process in selecting interval that gave the best total cost and lead PPM values. Their research methodology involved such procedure as going through the priority of critical parts in test machine, analyzing the danger or damage level using FMEA, calculating suitable replacement period with the instrumentality of reliable estimation. This study inferred that using the proposed simulation model will grossly reduce the reduce the lead PPM, cost of both good and lost products. Maintenance is now classified to be cost effective rather than a "forced and unnecessary" option for Companies (Atabak *et al*. 2014) [5]. Considerations in this literature are for both the business and technical facet of reliability and maintenance. Ghassem and Nasim (2015) [18] made a failure analysis in RCM systems applying the models of Pareto, fish bone and designing strategy of maintenance. The literature made it very revealing that finding an opposite solution and determining a fixed and practical strategy for improving the current level of maintenance while reducing defects resulting from technical problems of the equipment is one way to face capital, physical, and credit damages within large industries and small ones. However, Dahiru (2015) [8] opined that the maintenance of sound in power systems can be affected by the introduction of reliability modelling. It therefore, proposed the modelling of RCM is appropriate to enhance and optimize reliability. Therefore, the chosen RCM FMECA grid approach has advantages in realizing an automated control/ protection, self-healing, reducing the maintenance frequency leading to reduced cost and wear Dahiru (2015) [8].

For Dewangan *et al*. (2014) [10], the failure forms of steam induced vibration, unbalance of rotating components, mis-installation of turbine shafts, malfunctioning of the rotor, oil film instability of bearings, among other factors are liable for the unreliability and failure uncertainty of any power plant. Georgescu *et al*. (2010) [17] worked on the optimization of RCM used in transmissions & distributions network in power delivery using optimized maintenance models on the bases of reliability of a particular 20kV electric line, which resulted to an improved intervention number for the lines for different intervals and also an improved component intervention number for the line for a particular time interval. Oyedepo *et al*. (2014) [30] made a performance evaluation and economic evaluation (considering the outage power cost resulting from downtime) of a gas turbine plant in Nigeria over a 10 years period of 2001 – 2010. Sandor and Zoltan (2013) [33] worked on the implementing a distribution EA for parameter optimization in a cell nuclear detection project using a growth-based algorithm that is much faster than regular sequential versions. This led to the invention of evolution-based algorithm that could be employed in determination of some variables that can achieve better accuracy and precision than the existing parameters.

Dusan and Miroslav (2013) [11] determined optimal parameter of machine (cutting speed and feed), and the lowest reasonable cost for the turning processes were achieved using mathematical models. The Sequential Quadratic Programming (SQP) was utilized in checking the outcome of genetic algorithm and was observed tally with value of the machine cost, cutting feed and speed. The literatures proved the evolutionary algorithm to be more effective regarding execution time and the iteration number which brought about the conclusion that the EA is a modern technique of optimization for finding optimal values of functions with many variables. Abeysooriya and Fernando (2012) [1] similarly presented a canonical genetic algorithm (CGA) approach to the challenges of cut order planning. The result from the experiment of Abeysooriya and Fernando (2012) [1] are of the thought that the procedures and techniques proposed can produce a good improved outcomes compared to present methods of producing plans in the sector. EAs are robust, adaptive and powerful instrument for managers in solving optimization problems that can locate the global optimum with ease Dusan and Miroslav, (2013) [11].

Islam (2010) [20] described the applicability of RCM method in developing maintenance plan for a steam process plant, with consideration cost-effective plant parts maintenance reliability value as its major objective. The parts of this steam plant considered include steam distribution, fire-tube boiler, process heater, feed water pump, dryer etc. The RCM methodology of Islam (2010) [20] indicated that the MTBF for the plant equipment and the chance of sudden failure were significantly reduced. Even from the proposed labour program carried out, the labour cost/ year was reduced with about 25.8% using the proposed PM planning. Moreover, from the discoveries of the downtime cost, a savings of eighty percent (80%) of total cost was saved, as matched to the present procedure in the facility. The results indicated that around 22.17% of annual cost of spares can be saved from the proposed procedure. Willem and Rommert (2010) [35] predicted a classical approach to derive the number spare parts to stock, the spares shortage costs or the minimum fill rate are key factors. The major setback with this literature is the difficulty in finding the minimum fill rate or the estimation of the shortage costs, complications as result of RCM down-time costs of underlying equipment, and redundancy in the equipment. Due to these factors, the act of RCM data gathering, formation of a modelling structure for the more complicated system, and an approximate analytical measure were proposed to contain the challenges. Georgescu *et al*. (2010) [17] therefore developed an optimization preventive maintenance model for planning on the relics of RCM, through optimization of the maintenance activities number in a transmissions and distributions network of a power facility. The “renewal process” according to this literature, can restore the functionality of the system during technical limitation, improving safety and reducing cost of maintenance. The maintenance system optimization model on the bases of reliability, as applied with the 20kV electric line in Romania resulted in an improved number of maintenance interventions in the entire transmission/ distribution line, and an optimum maintenance intervention number on all part(s) of the transmissions and distributions line.

The Afam PLC was chosen owing to its vital contributions to Nigeria national power supply grid. Being first of the self-functioning power company in country, it has the tendency of acquainting the research process with multiple choices of techniques for collection of data. This study is aimed at an optimal RCM schedule that can bring into practice a cost-effective maintenance program in handling the most frequently occurring instances that lead to the failure of power plant under study. The objectives are to improve plant availability and reduce maintenance costs. Regarding novelty, this study analytically integrated both system and component reliability in its computation. It also uses a mixed method of analytical and computational approach. This gave room for comparison of the simulation results.

## 2. Methodology

### 2.1 Maintenance optimization based on RCM

This study projected an RCM planning technique that comprises of two (2) optimization steps as with the theories in the literatures of Bae *et al*. (2009) [6]. First, the total maintenance cost is minimized with the aid of the reliability matrix cost of maintenance while the reliability of the subsystem is been maximized at the time. In the view of this, the study utilized the method of multi-objective optimization technique. The function that represents the cost(s) of maintenance developed from this deduction can give the required information that proves the present characteristic of maintenance of the part(s) through creation of the vital factors and parameters of cost as given by the criteria of reliability, and maintenance capability of all parts. Also, this report explains the reliability function of the Gas Turbine (GT) applied in the power generation using the framework of reliability, between the applicable subsystems and parts, the second step of the optimization proposed in this study entails the allocation of maintenance reliability of every part to reliability function, overall cost of maintenance, and proposed subsystem reliability. Concerning the allotment of reliability functions, the optimization process here tends towards reducing the costs implications of maintenance, and same time meets requirement for the components’ reliability. The versatile EA is applied in this report to find the most acceptable reliability allocation means through painstaking searching the worldwide optimal in domain of nonlinear. This report finally proposes a procedure of maintenance derived by evaluating the time of maintenance for all the parts as derived from the apportioned reliability, and metrics, (Bae *et al*., 2009) [6]. This approach allocates the appropriate maintenance reliability value to all the part with the aid of optimized method as predicted by Bae *et al*. (2009) [6]. The maintenance costs are being minimized and its reliability requirements satisfied with the aid of this optimization technique. The problems of the optimization are given as in Equations (2.1), (2.1a) and (2.1b). The desired reliability of the system Rg is further defined in Equation (2.1c).

$$Minimize:\ C = \sum_{i=1}^{n} C_1(R_i) \tag{2.1}$$

$$Subjectto:\ R_g \leq R_s(R_i) \tag{2.1a}$$

$$R_i \geq R_{i,min} \tag{2.1b}$$

$$R_i \leq R_{i,max} \tag{2.1c}$$

$$i = 1,2,\ldots,n$$

Where, $R_g = R_s(t^*)$ (2.1d)

With C referring to the total costs of maintenance for the system, n is number of parts, Ci is cost(s) of maintaining the *i -th* part, Ri is *i-th* part reliability, $R_s$ is system reliability, R i,max is the i -th part's maximum reliability, and R i,min is the i -th part's minimum reliability. The constraint of inequality relates to the desired reliability of system, Rg, which is obtained from a sub-optimization process given in Equations (2.2), (2.2a) and (2.2b).

$$Minimize:\ C(t)$$

$$Maximize:\ R_s(t)t = t^* \tag{2.2}$$

$$Subjectto:\ t \geq 0 \tag{2.2a}$$

$$t \leq m_s \tag{2.2b}$$

The case where, t refers to the full or complete operating time (independent variables), t0 is the repair point per exchange time, ms is the Mean Time Between Failure (MTBF) of system. This is a demonstration of the system chance in maintaining a particular function without failing within a known time frame. The systems reliability Rs (Ri) can be calculated with the support of equations on the bases of reliability relationship existing between the system and its parts. An approximate method is proposed in this study for calculation of the expected reliability of system by constructing the relationship and artificial procedures based on networks, looking at the difficulties in applying the conventional methods.

The parts' reliability Ri is here taken as parameter of this design, The highest level of the reliability attainable is 0.9999 while the least reliability is evaluated on the bases of characteristics of the each factors considered. The factors are examined on the bases of the critical analysis conducted on the level of at which the failure of a given component or parts affect the systems function, and also the structural and/or functional importance attached to the part to the system. Therefore, as the relevance, cruciality and indispensability of a part increases the minimum reliability criteria also increase.

## 2.2 Maintenance cost function

The overall system costs of maintenance function having several components are derived in this segment. The overall cost is here given to be the sum total of operation costs of the various parts. The system's operational cost is here given as summation of the initial cost, repair cost, and the overall management costs. Therefore, the overall cost function can be given as clearly shown in Equation (2.3).

$$Totalcost(c) = \sum_{i=1}^{n} \left(C_{initial} + C_{repair} + C_{manage}\right) \tag{2.3}$$

With, $C_{initial}$ as the function for the overall initial cost, $C_{repair}$ as the function for overall repair cost, and $C_{manage}$ as the function for overall management cost.

Each cost functions is expressed as below:

The initial cost is represents the cost of purchase all through installation as stated in Equation (2.4).

$$C_{initial} = \sum_{i=1}^{n} W_{1i}\, n_i \tag{2.4}$$

Where, the $W_{li}$ is the weight factor of the initial cost i-th part, with n as the no of parts.

The respective part per cost of repair is estimated cost value for repair failure of every part excluding failure related costs not due to the failure of the *i-th* part. The summation of the respective cost of every component is the overall system repair costs. It is given as shown in Equation (2.5).

$$C_{repaiir} = \sum_{i=1}^{n} \left(w_{2i} * R_s * k_i(1 - R_i)\right) \tag{2.5}$$

Where $W_{2i}$ indicates the weight of repair cost factor for *i-th* parts, n is the number of parts, and $k_i$ equivalent to the number of redundancy in *i-th* part.

Management cost is defined as the overall administrative costs for system improvement. This is duly shown in Equation (2.6).

$$C_{manage} = \sum_{i=1}^{n} \left( w_{3i} k_i * \exp(1 - \widehat{m_i}) \frac{R_i - R_{i,min}}{R_{i,max} - R_i} \right) \tag{2.6}$$

Where, $\widehat{m}$ indicates the mainteability of the $i - th$ part.

Maintainability is the ease or tendency through which a part can be maintained (enhance performance). This is indicated in Equation (3.7).

$$\widehat{m_i} = \exp\left(-\frac{1}{MTTR} * t\right) \tag{3.7}$$

Where, t stands for the elapsed time of operations.

MTTR (Mean Time to Repair) is the time taken by a system part in an attempt to regain itself from failure that is assumed to be non-terminal (Bea *et al*., 2009) [6]. It is estimated through analysis of past failure data of the system.

All functions of maintenance cost must comply with items below:

- The costs of maintenance for reliability level desired for a part must be very high.
- The costs of maintenance for low desired-reliability level for a part must be very low.
- The curve of function of maintenance cost increases in directly balanced with the desired reliability of part.

When the component reliability is low, the maintenance costs are low as well, with a near uniform slope. In contrast, When the component reliability is high, the costs of maintenance rise by a rise in reliability. The maintainability effect in the given function of maintenance cost where the values ranges from 0 – 1, and also when the value is 1, the maintainability of *i –th* part is 100%. Even as some parts share similar reliability level, a part with high maintainability is said to be of a higher cost of maintenance than a part having low maintainability.

### 2.3 Sample model definition- GT reliability network

The RCM technique proposed needs a full model definition like BOM, FBD and operational data. The total system reliability $R_s$ is computed using reliability-based-equations, between the system and its parts. However, this popularly accepted technique for system reliability calculations is cumbersome to use in real life situation because of difficulty in differentiating the relationship in reliability among that of the system/ parts, ($R_s$) and the system itself, $R_i$ in a complicated systems like this case of the power generation systems. Because of these challenges, this report suggested the computation of indexes of reliability for all used components independently. This report has also studied the parts' failure rate, part's MTBF changes, following the time of operation for a GT system, using RGA technique of Bae *et al*. (2009) [6]. The overall rate of failure of all part for a period of time is calculated using Weibull distribution as represented in Equation (2.8).

$$\hat{\lambda} = \frac{n}{T^{\beta}}$$

$$\hat{\beta} = \frac{n}{n\ln T - \sum_{i=1}^{n} \ln T_i} \qquad (2.8a)$$

Where, $\hat{\lambda}$ stands for the scale parameter, $\hat{\beta}$ relates to the parameter shape, T indicates consumed or spent time of operation, and n the cumulative failure number.

The rate of failure of each part is computed using Equation (2.9) and Equation (2.10).

$$m_c = \frac{1}{\lambda} T^{1-\beta} \qquad (2.9)$$

$$\lambda_c = \lambda T^{\beta-1} \qquad (2.10)$$

Where.mc is used to represent the cumulative MTBF of parts, $\lambda_c$ represents cumulative rate of failure. The rate of failure $\lambda$ is expressed with Equation (2.11) and Equation (2.12).

$$\lambda = \frac{\varphi_n}{\beta_t} \qquad (2.11)$$

$$m = \frac{1}{\lambda} \qquad (2.12)$$

Where, $\varphi_n$ represents the no. of annual failure, $\lambda$ indicates the MTBR (hours), $\beta_t$depicting total operating time between maintenance in a year (inhours), and m the MTBF. Mathematically, reliability R(t) according to Dewangan *et al*. (2014) [10] is dependent upon the expected number of failure ($\lambda$) and the period or time (t), and is generally expressed with Equation (2.13), and $\lambda$ defined in Equation (2.13a).

$$R(t) = e^{-\lambda t} \qquad (2.13)$$

Where:

$$\lambda(\text{mean time to failure}) = \frac{\frac{\text{Total number of failure}}{\text{GT parts population}}}{\text{Operating periods(years)}} \qquad (2.13a)$$

The MTBF is the ratio of the total time of operation between annual maintenance to annual failure rate. It is therefore the average time the equipment can perform a particular function before the occurrence of an eventual unplanned failure. Thus, it implies the inverse of the rate of failure, and it can be expressed mathematically with Equations (2.13b) and (2.13c):

$$\lambda = \frac{\varphi_n}{\beta_t} \qquad (2.13b)$$

$$m = \frac{1}{\lambda} \qquad (2.13c)$$

Again, $\lambda$ is the expected failure number, $\Phi n$ refers to number of failures/ years, and $\beta t$ indicating total time of operation between maintenance/ year.

Reliability, R(t) refers to the ability of a system or device to perform its expected function optimally under given and specified condition at any given time frame (Dewangan *et al*., 2014) [10]. Thus, there is the likelihood that an equipment, a component, or a part operates under a failure-free mode over a given time, t. Therefore, R(t) can be expressed as Equation (2.14).

$$R(t) = e^{\left(\frac{-t}{m}\right)} \qquad (2.14)$$

### 2.4 Estimation of maintenance using evolutionary algorithm (EA)

The process flow of the optimization processes used in estimating properly the time of maintenance is detailed in Section 2.4.1 and 2.4.2. The allocation of the optimum reliability to all the selected parts in the system reliability boundary is done using the evolutionary algorithm. This technique is capable of finding workable optimal point in the non-linear domain (Bae *et al*., 2009) [6]. The EA is capable of finding the global optimum of a complex optimization problem of this kind. This report finally estimates the adequate maintenance time using reliability indexes and optimal reliability, obtained using inverse analysis of basic reliability function. The report also shared reliability of maintenance reliability to all the components using 2 optimization procedures which include the needed reliability of the system and maintenance reliability optimization.

### 2.4.1 Desired subsystem reliability determination (step 1)

The values are defined to be represented as functions by simply estimating the polynomials, while the optimization problem used for defining the subsystem reliability is defined in Equation (2.15), and constraints shown in Equations (2.15a) and (2.15b).

$$\begin{cases} \text{Minimize: } C(t) = 110.1\exp(-0.0433 * t) + 24.51\exp(-0.002204 * t) \\ \text{Maximize: } R_{GT}(t) = 99.82\exp(0.002204 * t)\, t = t^* & (2.15) \\ \text{Subject to: } t \geq 0 & (2.15a) \\ \qquad t \leq 288 & (2.15b) \end{cases}$$

Where, C(t) is the function for costs of maintenance w.r.t the operation time, RGT(t) is the function of the reliability of subsystem with respect to the time of operation, with t* as the optimum time of operation.

### 2.4.2 Maintenance reliability allocation (step 2)

This optimization problem is presented in Equation 3.16 using the needed reliability of subsystem derived in step 1. The respective reliability of the parts ($R_{ex}$, $R_{comp}$, $R_{turb}$, $R_{comb}$, and$R_{filt}$) makes up the design variable, while the costs of maintenance function become the objective function as given in Equations (2.3) to (2.7), which is as well the most fitted functions in the newly proposed algorithm. The target reliability of the subsystem is derived as 0.90, every $R_{i,max}$ is 0.999 and the respective $R_{i,min}$ are 0.930, 0.790, 0.810, 0.817, and 0.817 (Bae and others, 2009) [6]. The constant in the function is evaluated during the completion of the costs function. The indicated values with constant terms represent the weight factor for all maintainability cost and the cost function. For full concentration on the reliability's effects, the value of the constant (weight factor is pegged at constant 1). Equation (2.16) shows the design parameter, also known as components reliability and the objective function (the function of the costs). The applicable constraints as applied to Equation (2.16) is shown in Equations (2.16a) to (2.16k).

$$\underbrace{Minimize}_{R}\, C = \sum_{i=1}^{n} w_{1i} + \sum_{i=1}^{n}\left(w_{2i} * R_s * (1 - R_i)\right) + \sum_{i=1}^{n}\left(w_{3i} * \exp(1 - m_i)\frac{R_i - R_{i,min}}{R_{i,max} - R_i}\right)) \quad (2.16)$$

$$Subjectto: \quad R_{GT} \geq 0.90 \quad (2.16a)$$

$$R_{ex} \geq 0.930 \quad (2.16b)$$

$$R_{ex} \leq 0.999 \quad (2.16c)$$

$$R_{comp} \geq 0.790 \quad (2.16d)$$

$$R_{comp} \leq 0.999 \quad (2.16e)$$

$$R_{turb} \geq 0.810 \quad (2.16f)$$

$$R_{turb} \leq 0.999 \quad (2.16g)$$

$$R_{comb} \geq 0.817 \quad (2.16h)$$

$$R_{comb} \leq 0.999 \quad (2.16i)$$

$$R_{filt} \geq 0.817 \quad (2.16j)$$

$$R_{filt} \leq 0.999 \quad (2.16k)$$

$$i = 1, 2, 3, 4, 5$$

The EA is here applied using 100 as the population, with 0.25 as the cross-over rate (pc). The rate of mutation (pm) is 0.01, and a 25-bit number is used to indicate the various parameters. The Roulette-Wheel-Method (RWM) is adopted as the selection method (Bae *et al.*, 2009) [6]. A constructed reliability network is also used in the EA adopting Equations (2.14) to (2.16) in order to determine the GT-18 subsystem reliability. It is further coded using the in-built codes of EA tool of the excel solver.

## 3. Results and discussion

### 3.1 Input data

A joint method of quantitative and qualitative method is adopted to achieve higher reliability. The quantitative approach involves data collection (based on numbers and measurement) which were further interpreted and analyzed, while in the qualitative approach, observations, peer-to-peer interviews, and documentary analysis are used. The optimization of the current cost of maintenance is the centre of this study; this is sequel to the high overall maintenance costs leading to a corresponding high electricity tariff. To ensure consistency and high reliability, multiple data are collected, and with these data supporting each other, strong, interesting and exciting outcomes were generated. The method with which data are collected is here grouped under two categories:

**1. Primary data**

These include one-on-one interviews (with staff member(s) of the company), visual observations and measurements was carried out.

**2. Secondary Data**

To enrich the reliability of this study and validate the collected primary data, a thorough base of literature review was conducted both from publish and unpublished works which include Journals, conference papers, organization's documents, etc.

The obtained data of system operation comprises of the data of failure over time for the GT-18 system for the period of five succeeding years (2012 to 2016). The failed parts are duly coded in the data table alongside the cumulative failure numbers, and time of operation for the components. The data in this study are on the bases of 2 main assumptions as stated below:

1. That the parts are not exchanged for the given 5 years period duration.

2. If the parts are repaired owing to failure, then the repair automatically returns the parts or components to their initial or formal level of function before the failure.

A GT unit comprises of five major parts which include the air inlet filter, compressor, combustor, turbine, and the exhaust. The commonest source(s) of failure for a GT unit are failures resulting from dirty coils and blades, blocked suction lines, gas leakages, damage of the belt assembly resulting from excessive wear, etc. These failures might finally result in breakdown of GT unit, hence, directly influencing the systems reliability in terms of its efficiency and functionality.

The data of failure gathered over time from the GT unit (and the required BOM) for the five years period are indicated in Table 1. For ease of computation, the part codes 1, 2, 3, 4, and 5 will be used to represent the exhaust, compressor, combustor, turbine and air-inlet-filter respectively.

**Table 1:** 2012 to 2016 failure data for the GT-18 unit

| Part code | Failure No. (No's) | Operation Time (hrs) | Part code | Failure No (No's) | Operation Time (hrs) | Part code | Failure No (No's) | Operation Time (hrs) |
|---|---|---|---|---|---|---|---|---|
| 5 | 1 | 730 | 5 | 6 | 14645 | 4 | 9 | 27130 |
| 1 | 1 | 745 | 5 | 7 | 14994 | 2 | 8 | 29440 |
| 4 | 1 | 906.5 | 3 | 5 | 15007 | 5 | 12 | 32150 |
| 5 | 2 | 2014 | 2 | 4 | 15700 | 5 | 13 | 36120 |
| 3 | 1 | 2116 | 4 | 6 | 16230 | 5 | 14 | 37101 |
| 2 | 1 | 2677 | 1 | 4 | 17002 | 2 | 9 | 38112 |
| 5 | 3 | 3300 | 5 | 8 | 17223 | 3 | 9 | 39010 |
| 1 | 2 | 4205 | 2 | 5 | 17229 | 4 | 10 | 40105 |
| 4 | 2 | 4900 | 4 | 7 | 18215 | 1 | 7 | 40107 |
| 3 | 2 | 4950 | 5 | 9 | 19110 | 2 | 10 | 40225 |
| 4 | 3 | 5300 | 3 | 6 | 20111 | 5 | 15 | 40527 |
| 5 | 4 | 6425 | 3 | 7 | 20118 | 4 | 11 | 40925 |
| 2 | 2 | 6522 | 1 | 5 | 21200 | 5 | 16 | 41007 |
| 4 | 4 | 7200 | 5 | 10 | 21950 | 3 | 10 | 41090 |
| 1 | 3 | 7630 | 4 | 8 | 22500 | 5 | 17 | 41250 |
| 3 | 3 | 8750 | 3 | 8 | 22997 | 5 | 18 | 41940 |
| 5 | 5 | 9821 | 5 | 11 | 23107 | 5 | 19 | 42251 |
| 2 | 3 | 10432 | 2 | 6 | 25001 | 3 | 11 | 42330 |
| 4 | 5 | 11210 | 2 | 7 | 25900 | 1 | 8 | 43015 |
| 3 | 4 | 13203 | 1 | 6 | 26900 | 4 | 12 | 43295 |

### 3.2 Output data

These are generated using the proposed models in the earlier chapter in analyzing the input data obtained from the company under study. The results put into consideration the total number of failures for each of the five (5) critical components of the GT-18 system and the system as a unit in computing the MTBF, the failure rate as well as the reliability of the system. The section below detailed the computed results of the analysis.

### 3.2.1 Results of GT-18 system and components reliability computation

The values of the respective rate of failure of each part at the respective operating time are a well displayed in Fig 1. The approximate values so far obtained from historical failure records of the various part(s) of the GT-18 plant of the Afam power company Table 4 shows that for the exhaust λexh = 186 x 10-6, for the combustor $\lambda_{comb}$ = 283 x 10-6, for the compressor $\lambda_{comp}$ = 298 x 10-6, for the turbine $\lambda_{tur}$ = 277 x 10-6, and for the air-inlet-filter $\lambda_{aif}$ = 473 x 10-6. Also, the MTBF indicated values of 5376.9hrs, 3352.1hrs, 3527.5hrs, 3607.9hrs and 2112.4hrs for the exhaust, compressors, combustors, turbines and the air-inlet-filter respectively. The MTBF for the GT-18 unit indicated the value of 288hrs, and a failure rate ($\lambda_{GT}$) of 245 x 10-5. These results are duly shown in Table 2, it as well shows that the absolute error rate is averagely 1.43% which indicates that the computation is good, compared to the reliability analytical results of Jae Hoon *et al*., (2013).

From the subsystem reliability plot of the GT-18 system (Fig 1 and 2), the system's reliability against the consumed time is deduced. It is also deduced that a GT system requires a better efficient maintenance schedule than just the bases of MBTF, because the MTBF value of 288hrs did not meet the regulatory standard (Bae *et al*., 2009) [6]. Hence establishing concrete relationships between the GT-18 part's reliability and GT system's reliability is very urgent, using the outcome from Table 3. This is applied in the projected optimization model. The input is comprised of the five (5) parts reliabilities, while the output is the GT systems reliability.

The reliability data for the GT system and of the 5 parts is made or determined from reliability change diagram of Bae *et al*., (2009) [6] over a time/ period of 288hrs. The reliability data point number is fixed at 1024.

The final SSE of the procedure is computed to be 5.08E-1. A verification study is conducted to confirm that the rate of error between the inputs and outputs variable is very minimal. This confirmed that the outcome of the optimization process is good, comparing to the results obtained in Bae *et al*., (2009) [6]. This is represented in Table 2.

**Table 2:** GT-18 Part reliability computation

| Part code | No of failure | ϕn | βt | Developed system | | Reference system (AFAM PLC) | | Error (%) | Sum sq Error (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | λ | MTBF (m) | λ | MTBF (m) | | |
| 1 | 8 | 2 | 10753.8 | 0.000186 | 5376.875 | 0.000183 | 5464.4809 | 1.6032 | 50.87 |
| 2 | 10 | 3 | 10056.3 | 0.0002983 | 3352.0833 | 0.000293 | 3412.9693 | 1.7840 | |
| 3 | 11 | 3 | 10582.5 | 0.0002835 | 3527.5 | 0.00028 | 3571.4286 | 1.2300 | |
| 4 | 12 | 3 | 10823.8 | 0.0002772 | 3607.9167 | 0.000281 | 3558.7189 | 1.3825 | |
| 5 | 19 | 5 | 10562.8 | 0.0004734 | 2112.55 | 0.000468 | 2136.7521 | 1.1327 | |
| GT-18 | 60 | 15 | 4320 | 0.0034722 | 288 | 0.0034 | 292.4 | 1.5040 | |

Table 3 indicates the inter-linked reliability outcomes of each part using the EA (which is duly coded with the aid of the excel solver) as duly shown in Fig 1. The calculated reliability of the subsystem at 0.901 (90.1%), deduced by adopting the optimum reliability of every component is in conformance with the desired-reliability of the subsystem (that is the five components reliability), and constraints.

**Table 3:** Computation of the GT-18 system and part's reliability

| Part code | No of failure | ϕn | βt | λ | MTBF (m) | t | R(t) |
|---|---|---|---|---|---|---|---|
| 1 | 8 | 2 | 10753.75 | 0.000186 | 5376.875 | 305 | 0.94485444 |
| 2 | 10 | 3 | 10056.25 | 0.0002983 | 3352.083333 | 468 | 0.86969329 |
| 3 | 11 | 3 | 10582.5 | 0.0002835 | 3527.5 | 267 | 0.92710264 |
| 4 | 12 | 3 | 10823.75 | 0.0002772 | 3607.916667 | 523 | 0.86505776 |
| 5 | 19 | 5 | 10562.75 | 0.0004734 | 2112.55 | 345 | 0.84932807 |
| GT-18 | 60 | 15 | 4320 | 0.0034722 | 288 | 30 | 0.90107511 |

Even as the GT-18 subsystem structure varies, the maintenance cost differs in respect to the respective step following the parts' maintenance reliabilities. In other words, considering the normal steps without the reliability allocation, the respective parts' reliabilities which are 0.94485, 0.86969, 0.9271, 0.86505 and 0.84933, will satisfy GT-18 subsystem reliability of 0.901 (90.1%); and cost function of GT is 30.52. Putting the side constraints into consideration and carrying out simulation using the excel solver, The costs function was minimized from 30.52 to 25.5665, meaning a 16.2% cost is reduced if the proposed model is adopted. The values obtained for the GT system components reliability represented above are good as in comparison with the outcomes from Bae *et al*., (2009) [6], and also considering the current condition of operation of the GT-18 system.

### 3.3 Simulations

The number of failures for the GT-18 system and the components is shown in Fig 1, with GT-18 system having a total of 60 failures within the study period of 5 years. Remarkably, the exhaust component indicated the lease number of failure, while the air-inlet filter indicated the highest number of failures of all the components.

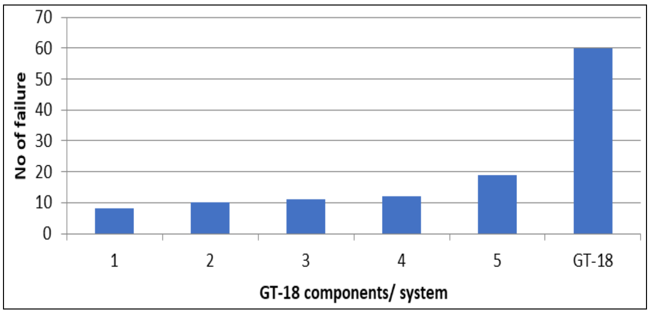

**Fig 1:** Plot of GT-18 system/ components against the number of failures

Fig 2 indicated a comparative chart of the MTBF of the developed system and the reference system of Afam PLC, of which the developed system indicated relatively lower values of MTBF as compared to the reference system, implying a remarkable development. Also, Fig 3 shows a plot of the failure rates of the GT-18 system and components comparing the developed system with the reference system of the facility.

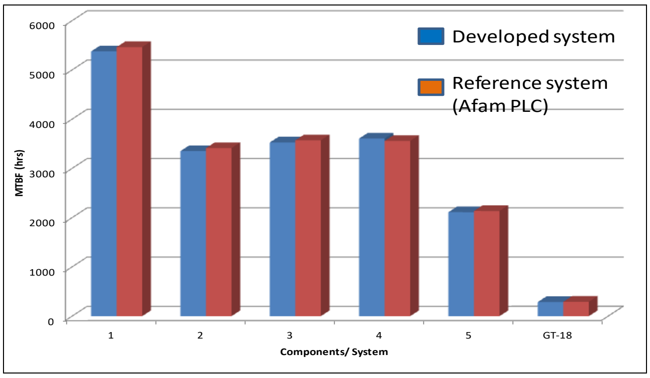

**Fig 2:** Comparative plot of MTBF of the GT-18 system/ components with respect to the developed and the reference system

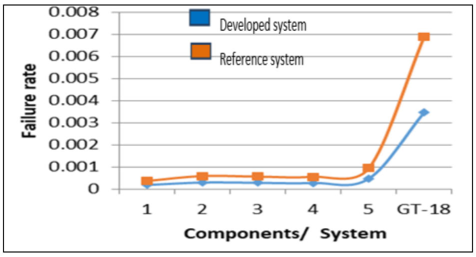

**Fig 3:** Comparative plot of failure rate of the GT-18 system/ components with respect to the developed and the reference system

Fig 4 shows the computed reliability of the GT-18 system and components. The exhaust indicated the highest reliability while the air-inlet filter indicated the least reliability.

The relationships between the sub-system reliability and the time of operation, t is represented in Fig 5.

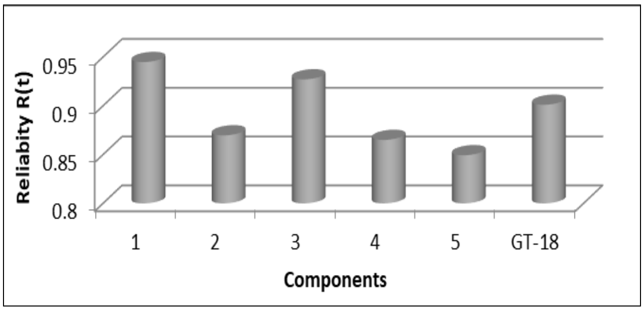

**Fig 4:** Plot of reliability vs GT-18 system/ components.

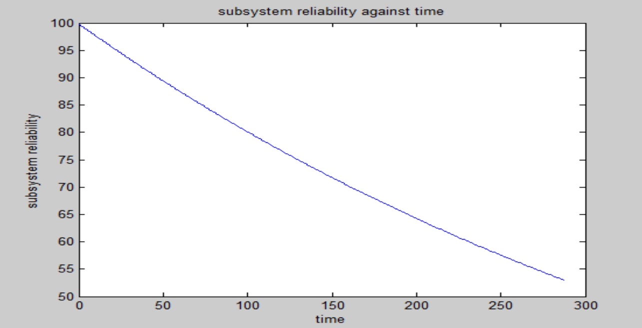

**Fig 5:** MATLAB Plot of subsystem reliability vs time

Using the instrumentality of the evolutionary algorithm component of the excel solver software, the simulation results of the cost function, with the initial (first) cost being 30.52 is optimized to 25.5665. This implies that 16.2% of the overall cost is saved.

## 4. Conclusion

### 4.1 Conclusion

In the consideration of safety and cost challenges, this study has revealed a sustainable RCM planning method applying computational methods, and applying same to the GT-18 system of the Afam plant. The main aim of this RCM technique applied in this report is to find the best cost (and time) of maintenance of the system.

The costs of maintenance function were foremost constructed to formulate the RCM-based optimization which shows the maintainability as regards the systems' part costs of maintenance by considering the cost elements of each part, as it relates to its first purchase, maintenance and management cost. On the second note, a Reliability Growth Analysis (RGA) and models were used to depict the reliability indicators, which comprise the rate of failure and th MTBF of the system and the parts. Thirdly, two (2) optimization models were proposed to actualize the optimum reliability of maintenance, and cost of the respective parts of the system.

Applying these models to the GT-18 system, 16.2% costs of maintenance was saved when the result of the optimization was compared with normal simulation, indicating a positive improvement in the logistics of maintenance.

Comparing the results obtained in this study to those obtained by Bae *et al*. (2009) [6], we can easily draw conclusions that similar results can be gotten despite the use of different approaches in solving optimization problems. The following conclusions can therefore be deduced:

- Following the reliability computation, the exhaust component is most reliable, while the air-inlet-filter is least reliable of all parts of the GT-18 system.
- All components of the GT-18 system needs to be in a full functional mode per time for the GT-18 system to be fully efficient.
- RCM is key in maintenance engineering and has a direct impact on both the operation and maintenance cost.
- RCM is a cost-saving maintenance planning technique that can be adopted in complex systems like power plants or similar facilities.
- Safety plays a key role in saving maintenance cost.

### 4.2 Contribution to knowledge

This report has projected a useful tool for maintenance planning, putting into consideration the factor of safety and economic viability, which are important considerations in maintaining and building systems that the dependable, and their essence are always appreciating especially in a complex system like the GT facility under study. It is therefore hopeful that the method proposed in this report will be useful in planning the maintenance of similar plants and other complex systems.

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