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Application Of Nested Design Statistical Model To A Triad Of Gas Turbine Historical Maintenance Data

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Abstract

This study is designed to provide a comprehensive nested design statistical approach in the maintenance programme of an electric power generating plant. Nested design statistical model was applied to a triad of gas turbine maintenance and production data collected from the original entries in the maintenance and production log book for a period of ten years.

Analysis of results for a two stage maintenance policy considered gas turbine (A) as treatment with F_{cal} equal to 91.647 and F_{tab} equal to 2.81. For the maintenance parameters individual turbine B(A), the calculated value (F_{cal}) is equal to 2.67 while F_{tab} is equal to 2.15. F_{cal} is found to be greater than F_{tab} in both cases and so hypothesis was rejected. In the case of production data, F_{cal} is less than F_{tab} and so hypothesis was accepted.

Our findings point to the fact that gas turbine is a robust means of generating electric power. This is manifested in the amount of maintenance work as well as running hours recorded. The outcome of the research showed that the organization has managed the system under standard engineering practices and this is the reason for good output over the ten-year period studied. The approach adopted in this study is novel and dependable.

Keywords: Nested, Sum of squares, Degree of freedom, Mean squares.

1. Introduction

In Nigeria, and indeed elsewhere, energy is so vital that those charged with the responsibility of its production have a duty to work towards overcoming the attendant challenges, including meeting the basic energy needs of a rapidly growing population. One way to meet this demand is to put in place appropriate maintenance management of power generation facilities including the management of human resources used. Articulating, harmonizing, summarizing and analyzing a mass set of data comprising many disparate observations taken over several years, in order to confer intelligent interpretation to the underlying operations and maintenance practice is a serious challenge that requires statistical sagacity and perspicacity.

The longitudinal data encompasses a tapestry of production and maintenance parameters. For example, total running time, electrical power produced, plant failure rate, plant down time, number of preventive maintenance, breakdown maintenance and condition monitoring maintenance, jobs done per month, number of man-hours utilized per month, and other related data require elaborate, well-crafted statistical experimental design to handle. The literature on installation, maintenance and operation of turbines intended for electric power generation is vast and varied in content and context. Few research studies have so far fitted elaborate nested experimental design to a disparate historical data pertaining to maintenance and operation of turbines used for electric power generation. This study is a novel attempt in the application of hierarchical experimental design to a bulk energy production, operation and maintenance data; thus demonstrating a unique statistical methodology that will open new frontiers in computational statistics. Gas, or combustion, turbines were originally developed in the 18th century [1]. Gas turbines are increasingly being used in power plants both in the utility and power sectors for their compactness, tremendous energy producing capacity, inherent flexibility, operational reliability, high performance and multiple fuel capability. Gas turbines are designed to be highly effective in producing aligned high thrusts [2] and [3]. In a gas turbine, atmospheric air is drawn in through intake duct into the compressor and delivered at a higher pressure to the combustion as explained by [4]. Some studies revealed that there are many factors that can influence equipment life, and these must be understood and accounted for in the maintenance planning. In fact, [5] and [6] stated Starting cycle (hours per start), power setting, fuel, level of steam or water injection, and environmental conditions as some of the key factors in determining maintenance interval requirements, as these factors directly influence the life of replaceable gas turbine parts. Relatedly, [7], and [8] confirmed that proper maintenance and operating practices can greatly affect the level of performance degradation and thus time between repairing and overhauling of gas turbines functionality is a direct result of the fine-tuned cooperation of many different components. A technique adopted for the analysis of the data collected from an experiment is the analysis of variance technique [9] and [10], which is useful for testing the hypothesis that all the treatment effects are same against an alternative that at least one treatment effect is different from others. This study aimed at reducing the bulky production, operation and maintenance data, obtained from a major electric power generating station, to a metadata in order to make them amenable to meta-analysis, a decision support tool that assist in understanding the level of maintenance effectiveness with respect to power generation level.

2. Materials and Method

2.1. Method

Maintenance and production data covering a period of ten (10) years pertaining to a triad of gas turbine labelled GT01, GT02 and GT03 were obtained from Warri Refinery Petroleum Company, a subsidiary of Nigerian Petroleum Development Company (NPDC). The data were extracted from the primary records of maintenance and production data for the organisation studied. The data were monthly observations dealing with general maintenance, breakdown maintenance, condition monitoring jobs, man-hour utilized, on the hand, and total running time, electrical power produced (MW), electrical energy produced (MWH), plant failure rate and plant down time (hrs), on the other hand. Each of the time series associated with variables above were obtained for each of the three turbines for ten years. Two-year monthly average, X_{ijk}, was computed for each of the maintenance parameter and production parameter respectively. The averaging procedure enabled the bulk of data to be summarized for effective application.

Nested or hierarchical design without cross-factors was fitted to the data obtained. This approach provided a means of examining the gas turbine as treatments while the maintenance parameters as well as production parameters as factors levels under the turbine. The gas turbines obtained power by utilizing the energy of jet burnt air and gas mixture (flue gases). The velocity of the jet is absorbed as it flows over several rings of moving blades which are fixed to a common shaft that extends into the alternator windings for electric power generation. The gas turbines operate on the principle of constant pressure cycle. They operate on a 24-hour basis and continuously generate electricity for WRPC operation. Furthermore, they were designed to function as a simple cogeneration and combined cycle plant. Consequently, the plants are subjected to random failures. On account of this, various types of maintenance schemes had been put in place to improve the system's reliability. On the other hand, daily power output and associated production data were regularly kept as journal records. It was from this book of original entries that the data for this study were extracted.

2.2. Production Data and Computations

Production data and maintenance data have separate experimental analyses that are identical mutatis mutandis. The production data comprises the following:

i. Total running time (TR)

ii. Electrical power produced (EP)

iii. Electrical energy produced (EE)

iv. Plant failure rate (PF)

v. Plant down time (DT)

On the other hand, maintenance parameters recorded include:

i. Number of preventive maintenance jobs done per month (M_1)

ii. Number of breakdown maintenance jobs done per month (M_2)

iii. Number of condition monitoring jobs done per month (M_3)

iv. Number of man-hour utilized per month (M_4)

Fig. 1 and 2 below show the experimental design for production and maintenance data respectively with each of the two having separate sketch for abstract and numerical schemes incorporating the data and specifying the elements of computation formula as necessary guide.

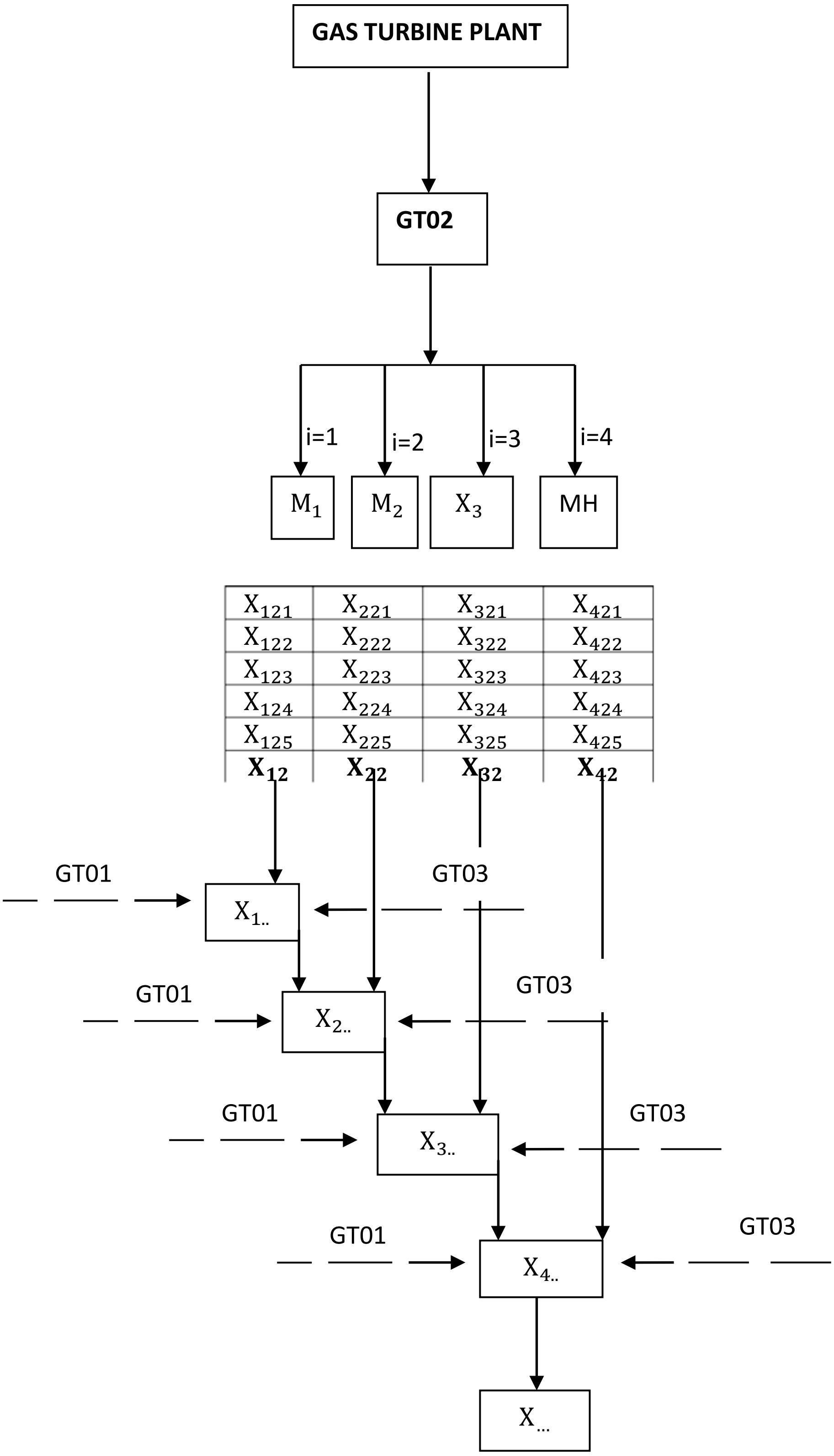
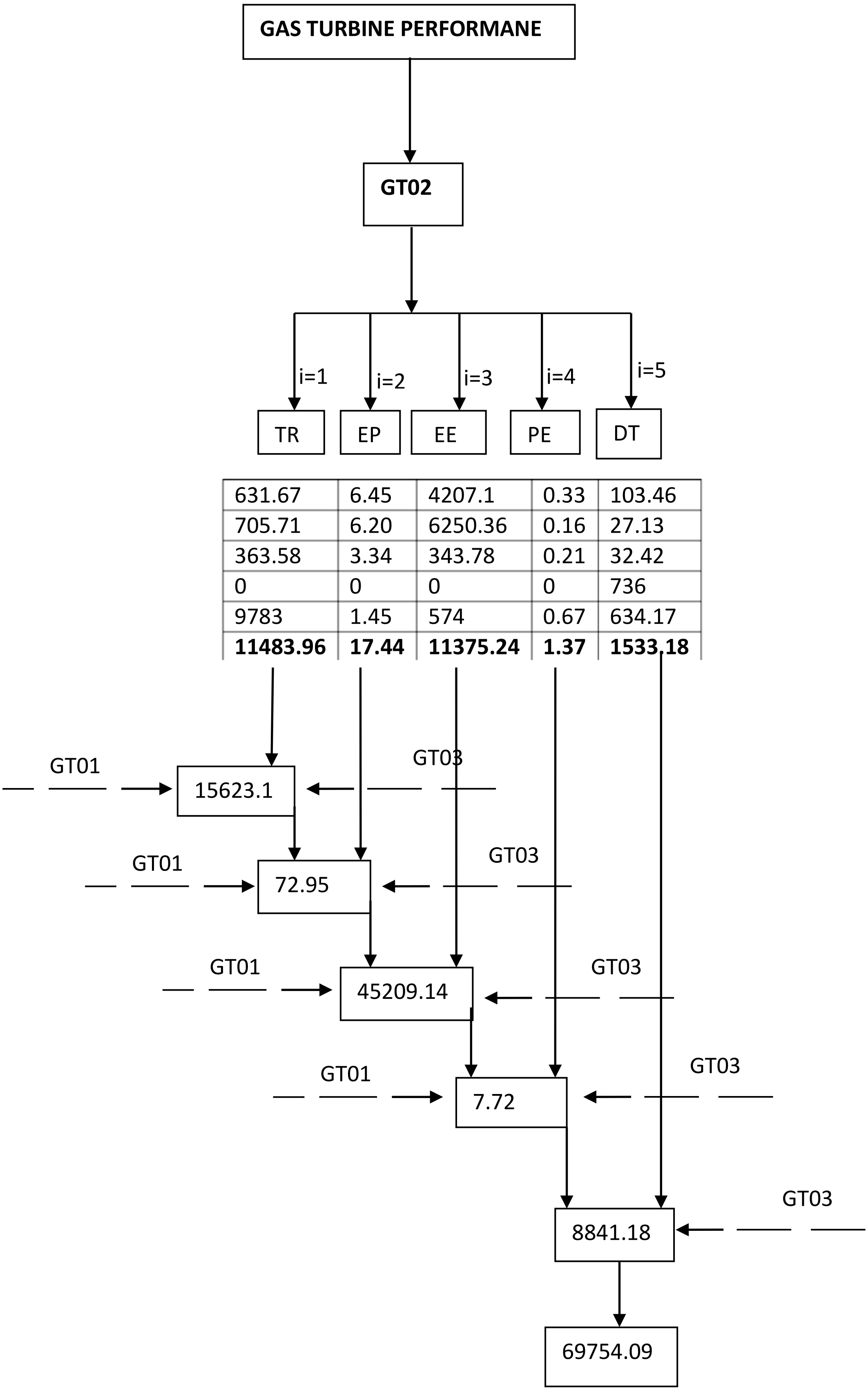


Fig.1: GAS TURBINE PLANT



TR	EP	EE	PE	DT
631.67	6.45	4207.1	0.33	103.46
705.71	6.20	6250.36	0.16	27.13
363.58	3.34	343.78	0.21	32.42
0	0	0	0	736
9783	1.45	574	0.67	634.17
11483.96	**17.44**	**11375.24**	**1.37**	**1533.18**

Fig 2: GAS TURBINE PERFORMANE

The statistical model developed for the study is of the form:

$$X_{ijk} = \mu + \alpha_i + \beta_j + \varepsilon_{ijk} \begin{Bmatrix} i = 1,2,3,\dots,I \\ j = 1,2,3,\dots,J \\ k = 1,2,3,\dots K \end{Bmatrix} \quad (1)$$

The computing formulae are as follows

$$SS_T = \sum_i^I = 1 \sum_j^J = 1 \sum_k^K = 1\, X_{ijk}^2 - \frac{\sum X^2}{IJK} P \quad (2)$$

$$SS_A = \sum_{i=1}^I \frac{X_{i\dots}^2}{JK} - \frac{X_{\dots}^2}{IJK} \quad (3)$$

$$SS_{B(A)} = \sum_{i=1}^I \sum_{j=1}^J \frac{X_{ij}^2}{K} - \sum_{i=1}^I \frac{X_{i\dots}^2}{JK} \quad (4)$$

$$SS_E = \sum_{i=1}^I \sum_{j=1}^J \sum_{k=1}^K X_{ijk}^2 - \frac{X_{\dots}^2}{IJK} \quad (5)$$

2.2.1. Statistical Computations

1. Maintenance Data

$$\mathrm{SS_T} = \sum_{\mathrm{i=1}}^{\mathrm{I}} \sum_{\mathrm{j=1}}^{\mathrm{J}} \sum_{\mathrm{k=1}}^{\mathrm{K}} \mathrm{X_{ijk}^2} - \frac{\mathrm{X^2}}{\mathrm{IJK}} \quad (6)$$

$$= \left\{(11.11^2 + 6.71^2 + 2.65^2 + \cdots + 7.29^2 + 1.17^2) - \left(\frac{4374}{4\times3\times2}\right)\right\} = 1009090.623$$

$$SS_A = \sum_{i=1}^{4} \frac{X_{i..}^2}{JK} - \frac{X_{\dots}^2}{IJK}$$

$$= \left\{\left(\frac{115.5^2 + 142.27^2 + 13.52^2 + 4103.5^2}{15}\right) - 318985.6\right\} = 805846.21$$

$$SS_{B(A)} = \sum_{i=1}^{3} \sum_{j=1}^{4} \frac{X_{ij.}^2}{K} - \sum_{i=1}^{3} \frac{X_{i..}^2}{JK}$$

$$= \{(49.17^2 + 55.85^2 + \cdots + 4.08^2 + 154.3^2)112483\} = 62557.34$$

$$SS_E = \sum_{i=1}^{3} \sum_{j=1}^{4} \sum_{k=1}^{5} X_{ijk}^2 - \sum_{i=1}^{3} \sum_{j=1}^{4} \frac{X_{\dots}^2}{IJK} \quad (7)$$

$$= 1328076.223 - 1187389.148$$

$$= 140687.075$$

Key results of Statistical Computation are summarized in ANOVA format as shown in table 1

Table 1: Results of Statistical Computations

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	**F$_{cal}$**	**F$_{tab}$**	**Decision**
Gas turbine (A)	805846.21	1-1 = 4-1=3	$\frac{SS_A}{I-1}$ = 268615.403	$\frac{MS_A}{MS_E}$ = 91.647	$F_{tab(A)} = 2.81$	$F_{cal} > F_{tab}$ Reject H$_0$
Maintenance parameters within individual turbine B(A)	62557.34	I(J-I) = 4(3-1)= 8	$\frac{SS_{B(A)}}{I(J-1)}$ = 7819.67	$\frac{MS_{B(A)}}{MS_E}$ = 2.67	$F_{tab[B(A)]} = 2.15$	$F_{cal} > F_{tab}$ Reject H$_0$
Error (E)	140687.075	IJ(K-1) = 4*3(5-1) = 48	$\frac{SS_E}{IJ(K-1)}$ = 2930.98	$\frac{MS_E}{MS_T}$ = 0.171		
Total	1009090.623	(IJK-1) = (4*3*5-1) = 59	$\frac{SS_T}{IJK-1}$ = 17103.231			

$$SS_T = \sum_{i=1}^{3}\sum_{j=1}^{5}\sum_{k=1}^{5} X_{ijk}^2 - \frac{\Sigma X^2}{IJK}$$

$$= \left\{(708.79^2 + 9.88^2 + 7188.46^2 + \cdots + 5.12^2 + 3298.6^2) - \left(\frac{(69754.09)^2}{3 \times 5 \times 5}\right)\right\}$$

$$= 322{,}192.4$$

$$\mathrm{SS_A} = \sum_{\mathrm{i=1}}^{3} \frac{\mathrm{X_{i..}^2}}{\mathrm{JK}} - \frac{\mathrm{X_{...}^2}}{\mathrm{IJK}}$$

$$= \left\{\left(\frac{15623.1^2 + 72.95^2 + 45209.14^2 + 7.72^2 + 8841.18^2}{25}\right) - 64875107\right\}$$

$$= 92866188.26$$

$$SS_{B(A)} = \sum_{i=1}^{3}\sum_{j=1}^{5}\frac{X_{ij}^2}{K} - \sum_{i=1}^{3}\frac{X_{i..}^2}{JK}$$

$$= \{(2548.21^2 + 32.24^2 + 2141.54^2 + \cdots + 3.39^2 + 154.3^2) - 157741295.9\}$$
$$= 768{,}938.489$$

$$SS_E = \sum_{i=1}^{3}\sum_{j=1}^{5}\sum_{k=1}^{5} X_{ijk}^2 - \sum_{i=1}^{3}\sum_{j=1}^{5}\frac{X_{ij.}^2}{K}$$

$$= 397068074 - 926679784.9s$$

$$= \ -529611710.9$$

The key results of the statistical computations for production data are collated in ANOVA result table 2.

Table 2: Results of Statistical Computation of Production Data

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	**F $_{cal}$**	**F $_{tab}$**	**Decision**
Gas turbine (A)	92866188.26	1-1 = 4-1=4	$\frac{SS_A}{I-1}$= 23216547.07	$\frac{MS_A}{MS_E}$ = -2.63	$F_{tab(A)} = 2.53$	$F_{cal} < F_{tab}$ Accept H_0
Maintenance parameters within individual turbine B(A)	768938489	I(J-I) = 5(3-1)= 10	$\frac{SS_{B(A)}}{I(J-1)}$= 76893848.9	$\frac{MS_{B(A)}}{MS_E} = -8.71$	$F_{tab[B(A)]}$ =1.99	$F_{cal} < F_{tab}$ Accept H_0
Error (E)	-529611710.9	IJ(K-1) = 5*3(5-1) = 60	$\frac{SS_E}{IJ(K-1)}$ = -8826861.85	$\frac{MS_E}{MS_T} = -1.966$		
Total	332192966.4	(IJK-1) = (5*3*5-1) = 74	$\frac{SS_T}{IJK-1}$ = 4489094.141			

3.0. Results

The hypothesis employed for both parts of the statistical computation are as follows:

1. Maintenance Regime

(a) *Individual Turbines (α_i)*

H_0: all $\alpha_i = 0$, i.e. the three turbines attracted equal maintenance attention.

H_i: some $\alpha_i \neq 0$, i.e. the turbines drew unequal maintenance attention.

(b) *Maintenance Parameters*

H_0': all $\beta_j = 0$, i.e. the mean of each of the four compatible maintenance parameters for the three turbines are the same.

H_1': some $\beta_j \neq 0$, i.e. there is contradiction among the compatible maintenance parameters.

2. Production Regime

a. Individual Turbines A (α_i)

H_0'': all $\alpha_i = 0$, i.e. the three turbines have the same reliability status.

H_1'': some $\alpha_i \neq 0$, i.e. reliability status differs among the turbines.

b. Reliability Parameters within individual turbines [B(A)]

H_0''': all $\beta_j = 0$, i.e. performance of each of the turbines favourable compares.

H_1''': some $\beta_j \neq 0$, i.e. the turbine outperformed each other.

3.1. Statistical Inference

Regarding maintenance administration, our historical data do not provide sufficient evidence for us to accept the two hypothesis H_0 and $H_0{}'$. Our conclusion therefore is that the three turbines attracted different maintenance treatments possibly on account of unmatched usage history among them.

Furthermore, although the same maintenance policy was adopted for all turbines; the resources expended on each seem to have differed significantly.

With respect to production output, there is no reason to suspect that each of the two null hypotheses are not true, based on the data employed in the analysis. Our inference therefore is that on one hand, each of the three turbines appears to be making fair and equal contribution to power generation. And that the downtimes and failure rates are random phenomena which appear to be arbitrarily distributed among the turbines. A possible explanation is that each of the turbines has the same age, similar reliability features and are subjected to the same range of duty (usage intensity and electricity load) over the length of time covered by the study. On the other hand, there appears to be no treatment variation among the production parameters nested under each turbine. The practical implication is that with each turbine plant, the total running hours, the electrical power produced, the electrical energy produced, the plant failure rate and plant downtimes appear to be similar for each turbine.

4.0. Discussion

Our analysis has shown that the failure rate, preventive maintenance scheduled, the corrective maintenance undertaken and the man-hour input, appear to have treatment effect. In other words, these maintenance parameters differ according to the plant in question. This effect becomes quite obvious when we take an overall view of the gas turbines without considering each separately.

One possible reason that can bring about this kind of different treatment is the randomness of failure rate that could give rise to differential corrective maintenance time, differential manpower or man-hour assignment and so forth. However, within plant, we observe an entirely different outcome. It becomes obvious that the same maintenance parameters remain unchanged. In other words, failure rate, man-hour, etc over the time period had remained fairly constant over the number of years considered.

We see here that the three turbines, over the number of years considered, appears to produce the same production outcomes. For example, the power output for each turbine appears to be at par over time. The same applies to other production parameters such as electrical energy produced, and total running time. Also, plant unreliability parameters such as downtime, failure rate appear to be evenly distributed among the three gas turbines.

However, when we consider these plant reliability parameters within each gas turbine, a different outcome appears to show. Expectedly, the parameters in question, namely; total-running times, electrical power produced, electrical energy produced, plant failure rate and plant downtime differ significantly. We do not even expect something different because the parameters in themselves are evidently not similar and unrelated. Taken together, we have seen that the three gas turbines appear to have similar distribution in terms of electrical power output over the years studied and that maintenance pattern had been significantly different for each plant on account of different failure rates and load conditions that the three plants experienced.

5.0. Conclusion

The nested design statistical approach has been successfully applied in the analysis of gas turbine operations with dependable outcome. Results obtained are conclusive and open new windows of opportunity for adequate management of power generating plants.

Acknowledgement

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