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# Effect of failure rates on system reliability of a gas turbine power plant

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**Abstract**
Reliability of a Gas Turbine power plant is a function of failure rate, maintenance (scheduled or forced), which in turns depends upon the Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) of equipment or systems, and which are further dependent on complexity in design, state, age of the equipment or system and to some extent on the availability of spare parts. This study tries to identify the vital component in the gas turbine power plant, establish the fact that failure rate inversely affects availability of gas turbine power plants, and thus, its reliability and also to use computer in timely evaluation of the actual figures of reliability, availability, failure rate, for any given power plant. It also assist thermal power plant managers establish a relationship between the types of maintenance adopted and plant reliability, and will also help in their day-to-day operating decisions. Observations from this analysis showed that increase in Failure Rate results in decrease in system reliability and availability. However, effective maintenance management is essential in reducing the adverse effect of equipment failure. This was done by accurately predicting the equipment failure such that appropriate actions can be planned and taken in order to minimize the impact of equipment failure on operation. Downtime losses and maintenance cost of a thermal power plant can be reduced by adopting a proper mix of maintenance and repair strategies on the failure rate of system reliability.

**Keywords:** reliability, mean time to failure, failure rate, mean time to repair, availability, gas turbine power plant

## 1. Introduction

The origin of machines began when man searched for a better way of achieving more work with little effort. It began with tools and farm implements, forged by man, and later evolved into simple machines which involves pulleys, levers and screws, and metamorphosed into complex machines. Harnessing the machine. Machines and equipment are indispensable part of our daily lives which makes life easy, comfortable and allows us to overcome huge challenges within a limited time. After such tasks, these equipment were cleaned, polished, sharpened, and the livestock were refreshed with food and rest. These things were done to maintain its usefulness, availability and dependency (reliability) when needed next time. This occurrence also applies to our modern day use of machines in industries, which require adequate care to maintain its effectiveness and efficiency. It is essential to recognise that we can take advantage of machines without risking its integrity and be able to accurately plan to stabilize its reliability as the necessity arises through maintenance, upgrade and monitoring of the equipment. Its advantages are to reduce unscheduled downtime, extend equipment's life, increase production, transition from "run to failure" to proactive lifestyle and improve equipment dependency. However, negligence to machine has being a major concern to Nigerian power sector, which has crippled our economy, industrial development and drove investors due to lack of power availability and reliability. These factors have also lead to reduction of production, excessive expenditure, equipment failure, and downtime in production.

### 1.1 The performance of the power plant

The performance of any power plant can be determined by any of these four elements;

i) Capability to satisfy functional needs
ii) Efficiency to effectively utilize the energy supplied
iii) Reliability to start or continue to operate
iv) Maintainability to quickly return to service after one failure

Therefore, Reliability analysis techniques have been gradually accepted as standard tools for the planning, design, operation and maintenance of thermal power plants. The function of a thermal power system is to provide electricity, mechanical energy and/or heat energy to its consumers efficiently and with a reasonable assurance of continuity and quality. The reliability of power supply is, therefore, related to the probability of providing customers with continuous service and with a voltage and frequency within prescribed ranges around the nominal values (Wang *et al.*, 2002; Wang and Billinton, 2003; Sikos and Klemeš, 2010) [10]. A modern thermal power system is complex, highly integrated and very large. Fortunately, the system can be divided into appropriately subsystems or functional areas that can be analysed separately (Gupta and Tewari, 2009; Kuo and Zuo, 2003; Lakhoua, 2009) [4, 6]. These functional areas are generation, transmission and distribution. Reliability studies are carried out individually and in combinations of the three areas. This work is limited to the evaluation of the generation reliability. Generation system reliability focuses on the reliability of generators in the whole electric power system

where electric power is produced from the conversion process of primary energy (fuel) to electricity before transmission. The generation system is an important aspect of electricity supply chain and it is crucial that enough electricity is generated at every moment to meet demand. Generating units will occasionally fail to operate and the system operations manager has to make sure that enough resources are channelled to bringing it back as fast as possible.
Reliability of the generation system is divided into adequacy and security (Hooshmand *et al.*, 2009; Valdma *et al.*, 2007) [5, 9]. System adequacy relates to the existence of sufficient generators within the system to satisfy the customer load demand or system operational constraints. Therefore, system security is associated with response of the system to whatever perturbation it is subjected to. In this study, the reliability evaluations will be focused on the generation system adequacy and will not take into consideration system security. A failure in a generating unit results in the unit being removed from service in order to be repaired or replaced, this event is known as outage. Such outages can compromise the ability of the system to supply the required load and affect system reliability. An outage may or may not cause an interruption of service depending on the margins of generation provided. Outages also occur when the unit undergoes maintenance or other scheduled work necessary to keep it operating in good condition. During the last decade, Nigeria has been restructuring her power sector, abandoning the former regulated monopolistic model which ruled the provision of electric energy during most part of this century (Obodeh and Isaac, 2011) [7]. The new "deregulated" structures are based on free market principles, favouring competition among private participants and new entrants into the power market such as Independent Power Producers (IPPs) and National Integrated Power Projects (NIPPs) and consumer choice. In this new environment, each generating company should provide its reliability and associated price to ensure customer satisfaction and personal preference. It is important therefore to ensure that equipment usage is maximised to save time and money Company of Nigeria (PHCN) but this supply has always been unreliable, with its many power outages. However, it is becoming increasingly necessary to guarantee plant reliability and economic efficiency in order to improve plant utilization.
The study will also show how factors like failure rate and repair rate affects RAM of the gas turbine power plant.

## 2. Materials and Methods

### 2.1 Methodology

The gathering of information played important role in this study. It will be difficult to come out successfully without implementing good ways of gathering information. Most of the information will be gathered from Transcorp Power Plc, Ughelli daily turbine operations record system that is using Human-Machine Interface (HMI) and by the use of questionnaires, personal interviews, the internet and research in good and comparative documents such as journal, textbooks, lecture paper, published and unpublished research works of notable professionals in Engineering, etc. The information that will be gathered will be used to analyse the failure rate, reliability, availability and maintainability of gas turbine power plants in Nigeria with special reference to Transcorp Power Plc, Ughelli.

The success of a research work like this depends on the availability of statistical data from the target company of case study and knowledge of the following theories and models;

### 2.2 Mean Time between failures (MTBF)

This is a measure of how long, on average, an equipment will perform as specified before an unplanned failure will occur. This may be measured by testing the system for a total period T, during which N faults occur. Each fault is repaired and the system put back on test. The repair time is excluded from the total test time T. The index MTBF is then given by:

$$\text{MTBF} = \frac{T}{N} \text{ (hours)} \quad (1)$$

This index is subject to sampling errors, since the system is observed for only a sample of its total life. Deduction from the result should allow for this error. Thus other things being equal, the system with the greatest MTBF is considered the most reliable.

$$\text{MTBF} = \frac{1}{F} \quad (2)$$

Where: F = expected failure rate.

### 2.3 Frequency of Failure or Failure Rate ($F$)

This is the number of faults per unit time. For Idealised system with constant failure rate for much of its working life, the failure rate is the reciprocal of the MTBF.

$$F = \frac{N}{T} \quad (3)$$

Where: $N$ = No. of failures between maintenance.
$T$ = total operating time between maintenance.

Also, $$F = \frac{1}{MTBF} \text{ (faults/hour)} \quad (4)$$

In all the above indices, the time needed to effect repairs on faulty components/units has not been considered. This is a very great deficiency, since there may be situations where short repair time is more desirable than high MTBF. Hence a better measure of reliability which considers repair time is needed.

### 2.4 Mean time to Repair (MTTR)

This is a measure of how long, on average, it will take to bring the equipment back to normal service status when it fails.

$$\text{MTTR} = \frac{\psi_t}{\emptyset_n} \quad (5)$$

Where: $\psi_t$ = total outage hours per year.
$\emptyset_n$ = No. of failure per year

Also, $$\text{MTTR} = \frac{1}{\mu} \quad (6)$$

Where: $\mu$ = expected repair rate.

$$\therefore \quad \mu = \frac{1}{MTTR} \qquad (7)$$

**2.5 Maintainability**
Maintainability is the probability that a system will be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures. (MTTR, MTBR)

**2.6 Availability (A)**
This is a measure of the percentage of time that an equipment is capable of producing its end product at some specified acceptable level. For a turbine in a power plant, availability is a measure of the fraction of time that it is generating the nominal power output. It is calculated by splitting all the time in a given period into two categories namely:
a) Up Time, UT: when the machine is in working order.
b) Down Time, DT: during which the machine is faulty or being repaired. The total period of observation is then UT + DT and availability or up time ratio becomes:

$$A = \frac{UT}{UT+DT} \qquad (8)$$

$$A = \frac{\mu}{F+\mu} \qquad (9)$$

Using equations (2) and (6) in equation (10), we have

$$A = \frac{MTBF}{MTBF+MTTR} \qquad (10)$$

$$\text{And } \bar{A} = \frac{MTTR}{MTBF+MTTR} \qquad (11)$$

Where $\bar{A}$ = unavailability
Equations (11) and (12) are for systems in which the component failure rate is constant (i.e. systems operating within their normal life period).
A further expression for the availability may be obtained in terms of the failure rate (F) and repair rate ($\mu$) as:

$$A = \frac{1/F}{1/F+1/\mu} = \frac{\mu}{\mu+F} \qquad (12)$$

$$\text{And} \quad \bar{A} = \frac{1/\mu}{1/F+1/\mu} = \frac{\mu}{\mu+F} \qquad (13)$$

However, in generating system, unit unavailability is obtained by a traditional method known as the Forced Outage Rate (FOR). This index is defined as the ratio of the Forced Outage Hours (FOH) to the sum of the Forced Outage Hours and the In-Service Hours (ISH):

$$FOR = \frac{FOH}{FOH+ISH} \qquad (14)$$

Further still, deficiency exists in all the enumerated indices since none models partial outages, Endrenyi 1978 made a good attempt by introducing a modified FOR called Equivalent Forced Outage Rate (EFOR), that takes partial alternative method that models both partial and full outages by looking at the outputs of the units directly, instead of the time of the units is proposed. The resulting index is availability factor discussed in the next section. Some of these primary indices are inputs for the calculation of the global indices. The choice of a particular index depends on the problem at hand and also on the data available.

**2.7 Availability Factor (AF)**
Due to the constrained nature of the sectorial reliability study in a mixed system, a reliability index called Availability Factor (AF) is used. This is defined as the ratio of the Available Capacity (AC) to the Installed Capacity (IC) of a generating station.

$$\text{i.e.} \quad AF = \frac{AC}{IC} \qquad (15)$$

**2.8 Reliability ($R_{(t)}$)**
Reliability is regarded as the ability of an equipment to perform its required function satisfactorily under stated conditions during a given period of time (Ireson *et al.*, 1996). Reliability can also be said to be a probability that the equipment is operating without failure in the time period t (Obodeh and Esabunor, 2011) [7].

$$R_{(t)} = e^{-\frac{t}{MTBF}} \qquad (16)$$

Using equation (2) in equation (17), we have

$$R_{(t)} = e^{-Ft} \qquad (17)$$

Where; t = specified period of failure-free operation

**2.9 Evaluation of Reliability Index**
In reliability evaluation, reliability indices could be assessed on either absolute or relative form. In the absolute use of an index, there should be a standard stated for the index in advance for the purpose of passing or failing. In the relative use of an index, a comparison is made, using the index, for different systems.

**2.9.1 Systems Relative Reliability Index Evaluation**
The reliability index evaluation of gas turbines in relative form is performed when system configuration or arrangement is considered. Systems are either arranged in series or parallel.

**3. Development of Flowchart**
A sample of the flowchart used in development of this program in shown in figure 1.

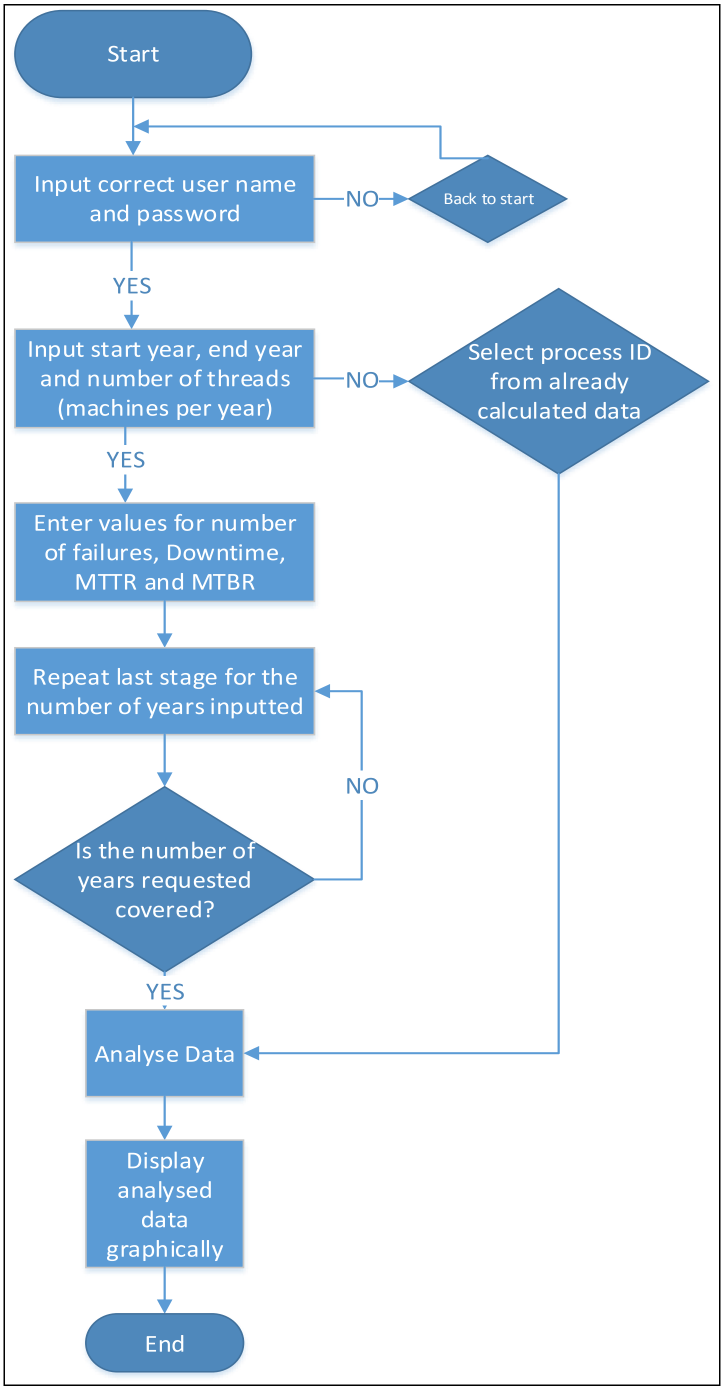


**Fig 1:** Program flowchart

### 3.1 Reliability Indices

The summary of reliability indices of Transcorp Power Plc Ughelli, Delta State, Nigeria for the period 2015 is summarised in table 1. A cumulative summary of the reliability indices for all the years under review is shown in table 1.

**Table 1:** Reliability Indices of Transcorp Power Plc Gas Turbines for year 2015

| Year | 2015 | | |
|---|---|---|---|
| | **Δ II** | **Δ III** | **Δ IV** |
| Number of Failures | 36 | 82 | 141 |
| Downtime (h) | 2934.45 | 3540.12 | 1821.06 |
| MTTR (h) | 1080.15 | 1025.3 | 280.13 |
| MTBF (h) | 1574.22 | 2378.86 | 413.97 |
| Failure Rate (F) | 0.0229 | 0.0345 | 0.3414 |
| Repair Rate (μ) | 0.0009 | 0.001 | 0.0036 |
| Availability (%) | 59.31 | 69.88 | 59.73 |
| Reliability (%) | 97.94 | 96.61 | 71.08 |

**Table 2:** Ten Year reliability indices of Transcorp Power Plant, Ugheli Delta State Nigeria

| Year | 2006 | | | 2007 | | | 2008 | | | 2009 | | | 2010 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** |
| Number of failures | 45 | 69 | 96 | 75 | 57 | 66 | 48 | 33 | 78 | 87 | 41 | 42 | 48 | 46 | 96 |
| Downtime(h) | 1415.3 | 3137.1 | 3548.6 | 1331.7 | 1068.06 | 3449.88 | 2754.9 | 2444.43 | 4302.9 | 1247.07 | 408.79 | 1861.14 | 603.9 | 839.38 | 2320.59 |
| MTTR(h) | 283.74 | 517.59 | 648.66 | 221.19 | 260.19 | 697.59 | 1053.27 | 1170.09 | 878.13 | 147.99 | 110.46 | 507.06 | 164.85 | 251.73 | 492.99 |
| MTBF(h) | 891.09 | 825.75 | 685.86 | 871.32 | 1598.13 | 844.17 | 932.48 | 1896.96 | 441.93 | 632.49 | 1797.01 | 1584.48 | 2540.52 | 2528.34 | 760.83 |
| Failure Rate, F | 0.0505 | 0.0836 | 0.14 | 0.0861 | 0.0357 | 0.0782 | 0.0515 | 0.0174 | 0.1765 | 0.1376 | 0.0228 | 0.0265 | 0.0189 | 0.0182 | 0.1262 |
| Availability % | 75.85 | 61.47 | 51.39 | 79.75 | 86.01 | 54.68 | 46.96 | 61.85 | 33.48 | 81.04 | 94.21 | 75.76 | 93.91 | 90.95 | 60.68 |
| Reliability % | 95.08 | 91.98 | 86.94 | 91.75 | 96.5 | 92.48 | 94.98 | 98.28 | 83.82 | 87.15 | 97.74 | 97.38 | 98.13 | 98.2 | 88.15 |

| Year | 2011 | | | 2012 | | | 2013 | | | 2014 | | | 2015 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** | **Δ II** | **Δ III** | **Δ IV** |
| Number of failures | 30 | 20 | 54 | 51 | 46 | 36 | 20 | 16 | 40 | 36 | 41 | 52 | 36 | 82 | 141 |
| Downtime(h) | 650.04 | 735.32 | 3864.9 | 1621.14 | 763.46 | 526.08 | 1382 | 289.08 | 986.32 | 693.16 | 707.88 | 698.58 | 2934.45 | 3540.12 | 1821.06 |
| MTTR(h) | 244.5 | 416.04 | 1170.9 | 470.34 | 833.67 | 1263.1 | 695.24 | 223.72 | 264.72 | 418.87 | 618.48 | 654.12 | 1080.15 | 1025.3 | 280.13 |
| MTBF(h) | 1736.4 | 2086 | 2513.5 | 1608.09 | 3798.96 | 2059.64 | 3701.22 | 794.64 | 789.84 | 632.72 | 1046.49 | 858.54 | 1574.22 | 2378.86 | 413.97 |
| Failure Rate, F | 0.0173 | 0.0096 | 0.0215 | 0.0317 | 0.0121 | 0.0175 | 0.0054 | 0.0201 | 0.0506 | 0.0569 | 0.0392 | 0.0606 | 0.0229 | 0.0345 | 0.3414 |
| Availability % | 87.66 | 83.37 | 68.22 | 77.37 | 82.01 | 61.99 | 84.19 | 78.03 | 74.9 | 60.17 | 62.85 | 56.76 | 59.31 | 69.88 | 59.73 |
| Reliability % | 98.29 | 99.05 | 97.87 | 96.88 | 98.8 | 98.27 | 99.46 | 98.01 | 95.06 | 94.47 | 96.16 | 94.12 | 97.94 | 96.61 | 71.08 |

### 3.2 Effect of Failure Rate on System Availability

Table 1 presents reliability indices for the gas turbines of Transcorp Power Ughelli from 2006 to 2014 according to their functional commissioning batches, Delta II, Delta III and Delta IV. Most of the failures were related to high temperature in the combustors, faulty cooling water fan motor, faulty compressor bleed valve, and exhaust over temperature, excitation trouble & generator differential lockout, low gas pressure or excessive vibration on the bearings.

In the years 2006, 2010 and 2015, Delta IV gas turbines experienced more failures due to high temperature in the exhaust collector caused by combustor problems; calibration problems of pressure gauges located at the exhaust collector and fuel filters premature cleaning due to premature clogging caused by poor natural gas quality. In the year 2012 and 2013, the Delta IV turbines had the least failure rate and downtime which invariably improved its Reliability and Availability. This is because of a thorough planned maintenance carried out on its turbines and overhaul of its auxiliary equipment.

In the year 2015, the main problems with Delta III turbines were related to the lubrication oil system, mainly the oil feeding pressure. These failures can be reduced if the maintenance procedure tasks involve periodical inspection and replacement of parts that were subjected to very high temperature and located in the hot gas paths (combustion chamber and turbine). However, sensors were installed in the oil pump to allow the use of a monitoring system to check oil pump vibration and oil temperature and flow. But a bi-monthly oil analysis should be implemented in order to check for the presence of metallic particles in the fluid that could be an indication of possible bearings parts wear.

The failure rate (F) is a reasonable measure for durability of generating devices like the gas turbines and indication for economical effectiveness of repairs. Effect of F on the system reliability and availability is revealed in Figure 2 and 3 respectively.

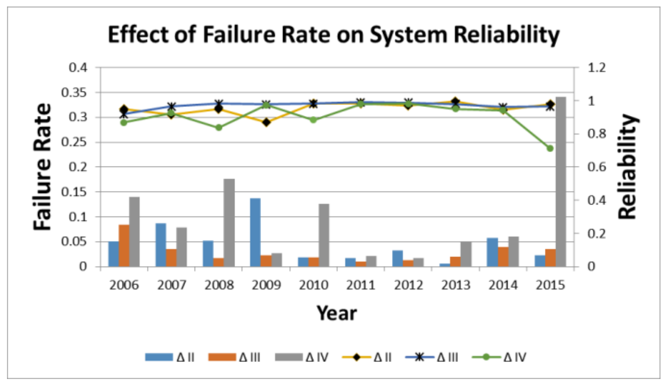


**Fig 2:** Effect of Failure Rate on System Reliability

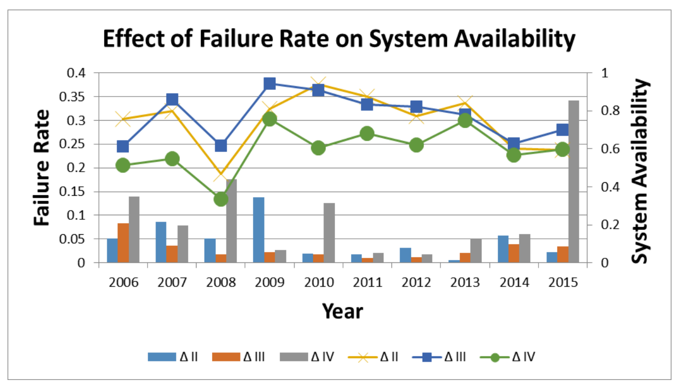


**Fig 3:** Effect of Failure Rate on System Availability

### 4. Conclusions

The analyses revealed that Delta IV gas turbines(Δ IV) has maximum failure rate ( max F) of once in 34 h in 2015 with system availability (A ) of 0.5973 (or 59.73%) and minimum failure rate ( min F) of once in 175 h in 2012 with availability of 0.6199(or 61.99%).While for Delta III gas turbines (Δ III), max F of once 836 h was obtained in 2006 with availability of 0.6147 (or 61.47%) and min F of once in 9600 h in 2011 with availability of 0.8337 (or 83.37%).And for Delta II gas turbines ($\Delta$ II), max F of once 13h was obtained in 2009 with availability of 0.8104 (or 81.04%) and min F of once in 5400h in 2031 with availability of 0.8419 (or 84.19%). In line with this, it can be deduced that increase in Failure Rate results in decrease in Availability. It is therefore recommended that thermal power plants in Nigeria, especially Transcorp Power Plc, Ughelli should imbibe effective maintenance management because it is essential in reducing the adverse effect of equipment failure to operations.

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