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Demand Decision Analysis Strategy Development for Gas Turbine Engine Based on the MTBF

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Abstract. At present, the most common methods employed by combined cycle power plants to schedule component planning are based on the data provided by the manufacturer or the experience of the power plant staff. However, the variations in usage and environment can lead to variations in the service life of the thermal component. Ignoring these external factors may result in a waste of resources and lack of inventory. In this study, a strategic decision analysis of Mean Time Between Failure-based (MTBF-based) gas turbine engine components needs is proposed. This analysis can assist power plant personnel in understanding the state of supply and demand for the special thermal components of specific gas turbine generators, thereby reducing the probability of the plant shutting down as the result of pending components and over-consumption of spares. Then, the overall costs of thermal component maintenance and management can be reduced.

Keywords: gas turbine generator thermal element, mean time between failures (MTBF), thermal power plant

1 Introduction

As the national economy develops, it becomes more dependent on power. Thermal power generation is a type of power generation. Therefore, it is essential for thermal power plants to obtain a reliable, sustainable and stable supply of electricity to run turbine engines [5]. To ensure the normal operation of a thermal power plant, the gas turbine blades and the combustion chamber located in the high-temperature zone of the facility must be regularly maintained and replaced.

In the past, because of the operation hours of the thermal components of the gas turbines, the replacement cycle of thermal components was determined in a thermal power plant [1]. But, the number of operational hours of a gas turbine unit is uncertain. In general, nuclear and coal-fired units place higher priority on a regeneration and repair schedule. In addition, the production of a new thermal component set or the renewal and repair processes of an old set might take anything from 8 months to 2 years. Therefore, it cannot be done within a normal overhaul schedule. Even with schedule planning, it is difficult to provide spare components for the gas turbine engine at fixed intervals of each overhaul. Therefore, a person must be designated to conduct regular tracking and estimation of hours of operation.

Information concerning thermal component planning is critical for the normal operation of power plants in Taiwan. The most common methods employed by combined-cycle power plants to schedule component planning are based on the data provided by the manufacturer or the experience of the power-plant staff after visiting recycling power plants. Detailed specifications from the manufacturer relate to

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the regular overhaul of each turbine engine, service life of turbine engine, standard life of the thermal component, and regeneration times. The power-plant personnel have to maintain each turbine engine regularly, in accordance with these specifications, to obtain reliable, stable, and continuous power supply. However, the accuracy of these specifications provided by the manufacturer has not been estimated.

Various usage and environments can lead to variations in the service life of the thermal component. Ignoring these external factors may result in a waste of resources and a lack of inventory. Although the thermal component may remain usable for an extended period, plant personnel dismantle the thermal component to perform regeneration or elimination based on data provided by the manufacturer. The high cost of thermal components may result in a waste of resources. In addition, the data provided by the manufacturer is only a reference. The thermal component may malfunction before the scheduled maintenance period. This type of inventory shortage may cause an entire gas turbine engine to shut down, and affect the normal operation of the power plant. Currently, the reliability of thermal components of power plants seldom needs to be considered. Estimations of actual thermal components used in the future do not take into account the impact of thermal component reliability, even though reliability affects their usage.

Reliability is one of the most important quality indicators employed during product usage. Previously, Sharma proposed a method to coat the thermal components to improve the reliability of each component [10]. It is possible to improve the quality of the process, yet the relation between the quality of design, quality of maintenance, and average life expectancy to the quality of reliability cannot be effectively estimated or confirmed. Therefore, a variety of distributions is used to improve the quality and reliability of power plant thermal components. Methods such as exponential distribution, Webster's distribution, and normal distribution, are used to explore the Mean Time between Failure (MTBF) of various generator thermal components, to understand the characteristics of the plant thermal components, and to obtain a more accurate forecast for the future use of components. This analysis is also used as one of the most important factors in making procurement decisions. The results obtained through the study determine the optimum balance between the procurement costs and normal operation of generators, enabling plant personnel to provide more accurate long-term planning for components, make precise financial budgets, and make full use of the residual value of every expensive thermal component.

Several different monitoring and diagnostic systems had been addressed in Volponi [11]. For whole thermal power plant, a residual life estimation procedure, based upon experimental and numerical methods has been introduced and applied by Jovičić et al. [3]. Yoshioka assessed the life of high temperature steam and gas turbine components in Japanese thermal power plants since the Great East Earthquake of 2011 [13]. The main purpose of this study is to build up an accurate system to predict the future state of thermal components and to establish more accurate Equivalent Operating Hours (EOH) based on the past record of operation hours, using MTBF statistical data. Procedural conditions for use of the Weibull distribution of MTBF [4] were established under these scheduling rules. An information system was developed to assist the research in this study. This information system was used to achieve a faster prediction of future component maintenance and replacement schedules. The comparison of those conventional relative researches is shown Table 1.

Table 1. The comparison of conventional relative researches

Compare Items / Researchers	Replacement Cycle Estimation Method	Reliability Improving Method	Inventory Cost
Original Management	Artifical Tracking & Prediction	Experience of Staffs	Most High
Jovičić et al. [3]	None	Residual Life Estimation	None
Volponi [11]	None	Monitoring and Diagnostic	Higher
Yoshioka [13]	None	Life Assessment	None
Sharma [10]	None	Componeents Coating	Lower
Tsai (Proposed)	MTBF	MTBF	Most Low

The rest of this paper is organized as follows. The proposed method is presented in Section 2. The system design and structure are discussed in Section 3. Two examples are used to discuss the proposed method in Section 4. The conclusion is offered in Section 5.

2 Methodology

The failure characteristics of a device can generally be divided into the run-in period, the useful life period, or the depletion period. A number of scholars started with the failure rate function, considered reliability behavior, and built several reliability functions [1]. Most of these functions are probability distribution functions of the failure, such as normal distribution, Weibull distribution, and exponential distribution [9]. Weibull distribution is more suitable for the aging-induced failure of products than the others [12]. Most of the failure-rate functions of the reliability models are related to functions of time. This means that failure-rate function can be a reliability function because there is a monotonous-relevant relationship between time and reliability [7]. The life of the device is evaluated with the Weibull distribution method, according to the scope of its use, including electronics, dielectric polymers, optical fiber communications, and other products. Failure of electrical insulation components in an electrical product are often caused by repetitive wear from thermal or mechanical force [4]. In this study, the proposed method is based on the MTBF to calculate the EOH and future overhaul dates.

2.1 Mean Life and Reliability

MTBF is the predicted elapsed time between inherent failures of a system during operation. MTBF can be calculated as the arithmetic mean time between the failures of a system [8]. In repairable systems, failures are considered as those out-of-design conditions that place the system out of service and into a state of repair. The MTBF reflects the ability of the product to maintain function and quality within a predetermined time. Specifically, the MTBF applies only to serviceable products. The MTBF can be obtained from the inverse of failure rate (the ratio of the total failure hours to the service life of a product). Therefore, the MTBF can be regarded as the ratio of the total accumulated working time to the number of failures [8].

The service life T of a product is a random variable. $P(T \geq t)$ refers to the probability of a product's service life T exceeding a certain time t. $R(t)$ refers to the reliability of a product's service life T exceeding a certain time t. $R(t)$ is equal to $P(T>t)$, and known as the reliability function [2, 4]. If $f(t)$ represents the probability function of the thermal component's life T, the probability function is shown as (1).

$$f(t)= P(T<t)=1-R(t),\ t \geq 0. \tag{1}$$

If the failure time of the thermal component is written by the random variable t, then the relationship between the probability function $f(t)$ and reliability $R(t)$ is shown as (2).

$$R(t)=1-f(t)=1-\int_0^t f(t')dt' . \tag{2}$$

The mean life refers to the average time of a certain object being operated or used from initial usage to failure or malfunction. Mean life is also referred to as MTBF [4]. If T represents the total operation times of products, and r is the total number of failures within the time T, then the MTBF can be expressed as (3).

$$\text{MTBF}=T/ r . \tag{3}$$

2.2 The Analysis of Common Average Failure Distribution

Sometimes the failure rate of the product life is not constant, and the purpose of the life test is not to realize the length of product life, but to estimate the loss of product life [12, 14]. In this study, the Weibull distribution is used to estimate the operation-to-failure hours of the gas turbine unit. Assuming the two parameters of the Weibull distribution are α (scale parameter) and β (characteristic life), and their probability functions are represented as (4):

$$f(t) = \alpha\beta t^{\beta-1} e^{-\alpha t^{\beta}} ,\ t>0,\ \alpha > 0 ,\ \beta > 0 . \tag{4}$$

The reliability function is shown as (5):

$$R(t) = e^{-\alpha t \beta} . \quad \textbf{(5)}$$

and the failure rate function is shown as (6):

$$h(t) = \alpha \beta t^{\beta - 1} . \quad \textbf{(6)}$$

After the shape parameter β and scale parameter α are obtained, the Equation (7) can be estimated.

$$MTBF = \int_0^\infty t \times \alpha \beta t^{b-1} e^{-\alpha t^\beta} dt . \quad \textbf{(7)}$$

The integral is the gamma distribution $\Gamma(1+1/\beta)$. Accordingly, MTBF is shown as (8).

$$MTBF = \alpha^{1/\beta} \Gamma(1+1/\beta) . \quad \textbf{(8)}$$

2.3 Weibull Distribution Moment Method

The β and α are the important parameters used to calculate MTBF in Equation (8). The generalized method of moment and the maximum likelihood method are the appropriate methods to estimate the β value and α value. Table 2 and Table 3 are the β value and gamma $\Gamma(1+1/\beta)$ obtained with the Weibull distribution. The mean and standard deviation of Weibull distribution can be expressed as (9) and (10) [4].

Table 2. The relationship between coefficient of variation CV and shape parameter β [4]

Coefficient of Variation CV	Shape Parameter β
1.5	0.71
1.00	1.00
0.75	1.35
0.5	2.10
0.45	2.35
0.43	2.50
0.35	3.11
0.25	4.55

Table 3. The relationship between shape parameter β and gamma distribution [6]

↓ β→	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
2.0	0.886	0.886	0.886	0.886	0.885	0.885	0.885	0.885	0.885	0.885
2.1	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885
2.2	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885	0.885
2.3	0.885	0.886	0.886	0.886	0.886	0.886	0.886	0.886	0.886	0.886
2.4	0.886	0.886	0.886	0.886	0.886	0.886	0.886	0.887	0.887	0.887
2.5	0.887	0.887	0.884	0.887	0.887	0.887	0.887	0.887	0.888	0.888
2.6	0.888	0.888	0.888	0.888	0.888	0.888	0.888	0.888	0.889	0.889
2.7	0.889	0.889	0.889	0.889	0.889	0.889	0.890	0.890	0.890	0.890
2.8	0.890	0.890	0.890	0.890	0.890	0.891	0.891	0.891	0.891	0.891
2.9	0.891	0.891	0.891	0.892	0.892	0.892	0.892	0.892	0.892	0.892
3.0	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.893	0.894	0.894
3.1	0.894	0.894	0.894	0.897	0.894	0.895	0.895	0.895	0.895	0.85
3.2	0.895	0.895	0.895	0.896	0.896	0.896	0.896	0.896	0.896	0.896
3.3	0.897	0.897	0.897	0.897	0.897	0.897	0.897	0.898	0.898	0.898
3.4	0.898	0.898	0.898	0.898	0.898	0.899	0.899	0.899	0.899	0.899
3.5	0.899	0.899	0.890	0.890	0.890	0.890	0.890	0.890	0.890	0.891

$$E(T) = \alpha^{1/\beta \Gamma(1+\frac{1}{\beta})} = \eta \Gamma(1+\frac{1}{\beta}) . \quad \textbf{(9)}$$

$$D(T) = \alpha^{-1/\beta}\sqrt{\Gamma(1+2/\beta)-\Gamma^2(1+1/\beta)} = \Gamma\sqrt{\Gamma(1+2/\beta)-\Gamma^2(1+1/\beta)}\,. \quad \textbf{(10)}$$

Therefore, the variation coefficient CV can be expressed as (11).

$$CV(T) = D(T)/E(T) = \sqrt{\Gamma(1+2/\beta)/\Gamma^2(1+1/\beta)^{-1}}\,. \quad \textbf{(11)}$$

The sample mean $\overline{T}$ and standard deviation S can be obtained from a sample size of n (t_1, t_2, ..., t_n). Then the coefficient of variation CV of the samples can be obtained from $S/\overline{T}$. If the sample mean $\overline{T}$ and standard deviation S are obtained from a sample size of n (t_1, t_2, ..., t_n), then the coefficient of variation CV($S/\overline{T}$) of the samples can be obtained, and its correlation can be derived as follows:

Sample mean: $\overline{T} = \sum_{i=1}^{n}(T_i/n)\,.$ **(12)**

Standard deviation: $S = \sqrt{n\sum_{i=1}(T-\overline{T})^2/(n-1)}\,.$ **(13)**

Sample coefficient of variation: $CV = S/T = \sqrt{(\Gamma(1+2/\beta)/\Gamma(1+1/\beta))-1}\,.$ **(14)**

According to the Weibull distribution, α can be estimated as (15), and gamma can be estimated as (16). Finally, *α*, *β*, and gamma $\overline{\Gamma}$ are substituted into (8), after which MTBF can be obtained.

$$\overline{\alpha} = \frac{1}{n}\sum_{i=1}^{n} t^{\overline{\beta}}\,. \quad \textbf{(15)}$$

$$\overline{\Gamma} = \overline{\alpha}^{\frac{1}{\overline{\beta}}}\,. \quad \textbf{(16)}$$

2.4 Estimation of MTBF of Gas Turbine

Fig. 1 describes the process of calculating MTBF, which is obtained in accordance with Fig. 1 and Table 4. In Table 4, D_i represents the overhaul dates. Each cumulative overhaul EOH is represented by E_{1i}. E_{2i} represents the interval EOH of each overhaul date of each unit. When the overhaul intervals EOH of each unit are obtained, the CV value can be determined using a statistical Equation (coefficient of variation).

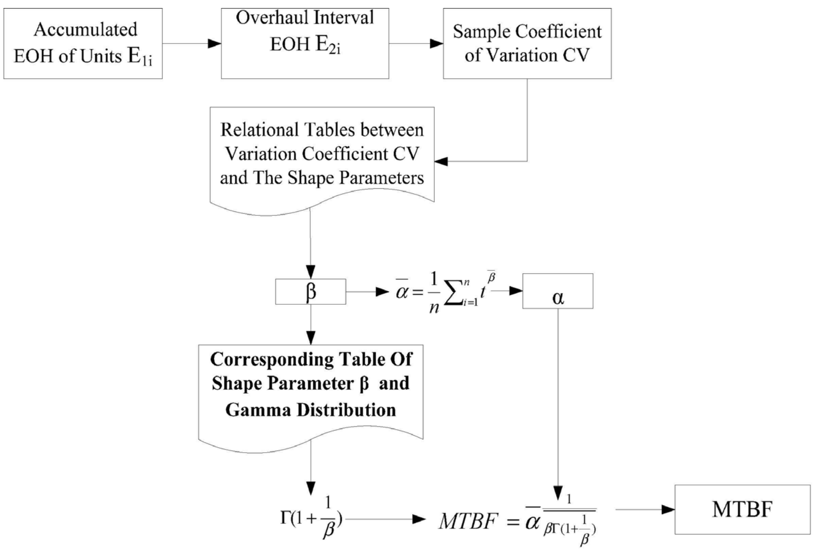

Fig. 1. Processes of MTBF assessment

Table 4 The unit overhaul interval EOH

Items	Overhaul Date D_i	Unit Cumulated EOH E_{1i}	Overhaul Interval EOH E_{2i}
1	D_1	E_{11}	
2	D_2	E_{12}	$E_{21}=E_{12}-E_{11}$
3	D_3	E_{13}	$E_{22}=E_{13}-E_{12}$
...	...	...	...
n-1	D_{n-1}	E_{1n-1}	$E_{2n-1}=E_{2n-1}-E_{2n-2}$
n	D_n	E_{1n}	$E_{2n}=E_{2n}-E_{2n-1}$

In the case of $CV = S/T = \sqrt{(\Gamma(1+2/\beta)/\Gamma(1+1/\beta) - 1}$, β can be obtained from the given CV. Then, the value of β can be obtained from (16). In addition, $\Gamma(1+1/\beta)$ is derived according to Table 3. Finally, α, β and gamma $\overline{\Gamma}$ are substituted in $MTBF = \overline{\alpha}(1/\beta\Gamma(1+1/\beta)$, after which MTBF is obtained.

The purpose of this study is to predict future overhaul dates. Moreover, the MTBF is unknown with regard to actual running time. Therefore, the proportion method is used to estimate the future date of overhaul *t*. According to the future overhaul dates predicted, the interval proportion of latest record date and starting (ignition) date are used for prediction.

$$D_2=EOH_2*D_1/EOH_1. \tag{17}$$

D_1: The interval of latest record date to *the latest overhaul date.*
D_2 : Next overhaul dates.
EOH_2: The EOH interval of the next overhaul hours to the latest reading EOH.
EOH_1: The estimated EOH.

3 System Design and Structure

The future overhaul-date factor of the unit is obtained from the Weibull distribution moment in this study. The other scheduling factors are fixed constants, and will be used to design a scheduling system to facilitate the calculation of future overhaul dates, to simplify the process of manual scheduling.

There are four essential factors that decide a thermal component schedule. They are the future unit-overhaul-date factor, the requisition or procurement time factor, the storage time factor, and the regeneration time factor.

(1) The future overhaul-date factor: This is the only predicted factor in the system design. In addition, the factor explored in this study can be obtained in accordance with the Weibull distribution-moment method.

(2) Requisitions time factor: It takes at least 2 years from the initial order to produce a new thermal component, as result of the unique materials required. Thus, the next overhaul date must be predicted to find the optimal procurement timing.

(3) The storage time factor: This is the date that the thermal component is purchased and placed into the inventory.

(4) Regeneration time factor: When the unit is overhauled, the thermal component must be removed for repair and maintenance. However, different thermal components have different methods of maintenance, as shown by the example of the combustor basket, with a 180-day regeneration period. Moreover, each thermal component has its own service-life limit, such as the 24000 EOH of the combustor basket. If we calculate that the unit must be maintained after running 7323.37 EOH, the thermal component can be used only three times and regenerated twice.

In this study, MTBF is used to perform the gas turbine generator thermal component decision analysis. A decision support system is constructed based on the proposed theory. As long as the related factors, such as unit overhaul date and the hours of failure, are input, the procurement timing, replacement timing, and the amount of inventory needed can be accurately predicted. There are three modules are present in this system: the basic information module, usage management module, and the schedule module.

There are three main systems in the basic information module, including the unit information system, the thermal component-classification information system, and the thermal component information system. The unit information system (Fig. 2) manages the basic information of units in each power plant, such as unit name, manufacturer, recommended overhaul EOH, and operational life. The thermal component-classification information system (Fig. 3) is used to manage the type of thermal components. The number of the thermal component is the primary key. The model and type of component are the unique keys. The thermal component information system (Fig. 4) is used to record the information of each thermal component.

Fig. 2. Unit information system

Fig. 3. Thermal component classification information system

Fig. 4. Thermal component information system

There are three main systems in the usage management module, including the installation management system, the dismantling management system and the combination of sets management system. The installation management system (Fig. 5) is used to record the date and EOH of thermal component installed in units in each overhaul timing. The combination of sets management system (Fig. 6) is used to record the date and EOH of the thermal component dismantled out of units in each overhaul timing. The combination of sets management system (Fig. 7) can manage the complete set for each thermal component. For example, a complete set would include 12 pieces. Sometimes, one of the 12 pieces is considered too damaged and is irreparable, so only 11 pieces would be renewed. A piece must be removed from another thermal component set to make the first set operational. According to Fig. 7, the thermal component is composed of 11 pieces of No. 007 and one piece of No. 012. Therefore, No. 007 is mixed with 11 pieces of No. 007 and one piece of No. 012.

Fig. 5. Installation management system

Fig. 6. Dismantling management system

Fig. 7. Combination of sets management system

The user can set various parameters, such as the estimated date of next overhaul timing, regeneration timing, and type of thermal component. The schedule module automatically predicts the future schedule of procurement timing, replacement timing, and the amount of inventory needed. The predicted result can be exported into Excel files. The user can then modify the future predicted schedule in these Excel files.

(1) The schedule is composed of the actual history record and future predicted record (Fig. 8). Consider an example of GT13-U. No. 006 was installed on January 2011 and dismantled on December 2011. Both of the two timing data are actual history records. No. 010 was installed on January 2012 and dismantled on October 2013. The data of January 2012 belong to actual historical records, and the data of October 2013 belong to future predicted records.

Fig. 8. The record type of schedule

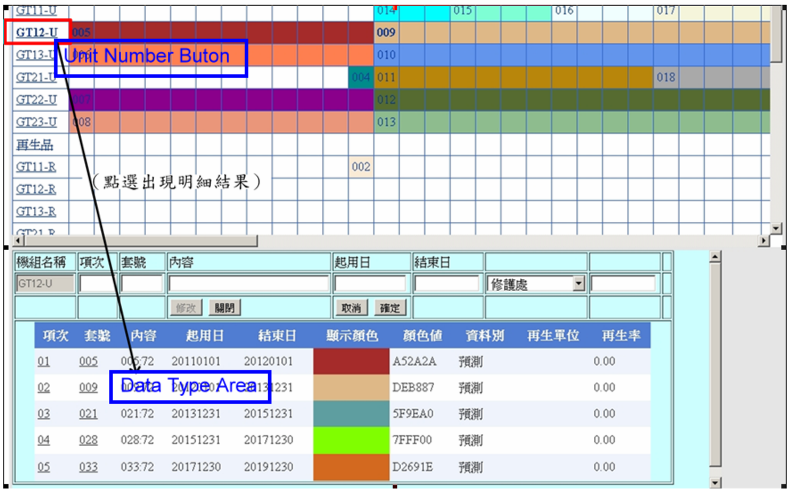

Fig. 9 How to display the data type area of system

(2) When the [unit number] button is pressed, each of the dismantling dates is displayed in the bottom table. In the data-type area (Fig. 9), the actual historical data can be distinguished from the predicted data.
(3) Finally, the system provides the function to export the schedule to Excel files.

4 Examples

In this section, two examples are illustrated to explain MTBF and forecast scheduling using the developed program.

4.1 Actual Average Failure Time Calculation of the GT41 Gas Turbine Generators of a Southern Thermal Power Plant

In the first example, the GT41 gas turbine generators of a southern thermal power plant are illustrated to calculate the MTBF in terms of the Weibull distribution-moment method. Table 5 shows the overhaul data recorded for the GT41 from the starting fired date (the date that new units began to run) to the present. The data was recorded from 30 January 2004 to 23 March 2011 in a southern thermal power plant.

Table 5. GT41 thermal unit overhaul records

Items	Ovehaul Date	Cumulated EOH of Unit Overhaul	Last Unit Overhaul EOH	Interval EOH
1	20040130	8948	0	8948
2	20041113	15666	8948	6718
3	20050606	20268	15666	4602
4	20060106	24259	20268	3991
5	20070105	32118	24259	7859
6	20071226	40850	32118	8732
7	20081128	49652	40850	8802
8	20100105	57709	49652	8057
9	20110323	65970	57709	8261

The results obtained were as follows:

(1) Mean failure hours: $\overline{T} = \sum_{i=1}^{n} T_i / n = 7330$.

(2) Standard deviation: $S = \sqrt{(\sum_{i=1}^{n} (T - \overline{T})^2)/(n-1)}$ =1744.544.

(3) Coefficient of variation: $CV = S/T = \sqrt{(\Gamma(1+2/\beta))/(\Gamma(1+1/\beta)) - 1} = 0.238$.

(4) In Table 2, the shape parameter is =4.55.

(5) Scale parameter: $\overline{\alpha} = (1/n)\sum_{i=1}^{n} Ti^{\overline{\beta}}$ = 601870160793069000.00.

(6) $\overline{\Gamma} = \overline{\alpha}^{\frac{1}{\overline{\beta}}}$ =8083.19.

According to Table 3, $\Gamma(1+1/\beta)$=0.906, MTBF=$\overline{\alpha}^{\frac{1}{\overline{\beta}}\Gamma(1+\frac{1}{\beta})}$ =8083.19*0.906 = 7323.37. Therefore, the GT41 gas turbine generator needs to be maintained after running for approximately 7323.37 EOH. The unit overhaul date is similar to the regular maintenance performed on a car. It must be disabled for maintenance after operating from 8000EOH to 16000EOH and replaced by thermal components. The operation-to-replacement hours of the units are known, but the actual running time is unknown. Therefore, the proportion method was used to estimate the future overhaul date. In the present study, the proportional interval of the latest recorded date of ignition was used to estimate the projections. Table 6 shows the interval of EOH between the ignition date and latest recorded date.

Table 6. The interval of EOH between start fired date and latest record date

Items	Ovehaul Date	Cumulated EOH of Unit Overhaul	Last Unit Overhaul EOH	Interval EOH
1	20030502	0	0	0
2	20110323	65970	65970	65970

According to Equation (17), D_2=EOH_2*D_1/EOH_1= [(2011/03/23]-(2003/05/02)) *7323.4/65970=319.9 (*days*). If calculated on an annual basis, *Years*=320/365= 0.88 *years*, then the overhaul period is approximately 0.88 years.

Confidence intervals testing. A confidence interval is a range of numbers believed to include an unknown population parameter. Associated with the interval is a measure of the confidence that the interval does actually contain the parameter of interest. In this case, a 95% confidence level was set and the confidence intervals were obtained as follows:

(1) $\overline{X} \pm t_{n-1,\alpha/2} S/\sqrt{n} = 7330 \pm 1.96 * 1744.544/\sqrt{9} = 7330 \pm 1340.973$.

(2) $6190.231 \le u \le 8469.769$. The value 7323.4 EOH obtained from this study and the value 8000 EOH published by the manufacturer both lay within the confidence levels.

Hypothetical testing for 7323.37 EOH obtained from Weibull distribution moment method. In this section, hypothetical testing was performed to determine whether the value 7323.4 EOH is correct or not. First, it was assumed that the combust basket running at most 7323.37 EOH must be replaced and maintained, or an overhaul will occur.

(1) H_0: *u*<=7323.37, H_1: *u*>7323.37.

(2) Then, the value of probability *P* is calculated. The alternative hypothesis symbol is '>', so this test adopts the right-tailed test.

$$P(\overline{X} \ge \overline{X}^* \mid u = 7323.37) = P((\overline{X} - 7323.37)/(1744.544/\sqrt{9}) \ge (7330 - 7323.37)/(1744.544/\sqrt{9}))$$
$$= P(Z \ge 0.011401) = 0.4996(0.5 - 0.004) > \alpha = 0.05$$

(3) Because the value of probability *P* = .4996 is greater than α=0.05, the null hypothesis is not rejected. Therefore, when the combust basket runs for approximately 7323.37 EOH, it must be replaced and maintained, or an overhaul will occur.

Hypothetical testing for 8000 EOH published by the manufacturer. Next, it was assumed that the combust basket running at most 8000 EOH must be replaced and maintained, or an overhaul would occur.

(1) H_0: *u*<=8000, H_1: *u* > 8000.

(2) Then the value of probability *P* is calculated. The alternative hypothesis symbol is '>', so this test adopts the right-tailed test.

$$P(\overline{X} \ge \overline{X}^* \mid u = 8000) = P((\overline{X} - 8000)/(1744.544/\sqrt{9}) \ge (7330 - 800000)/(1744.544/\sqrt{9}))$$
$$= P(Z \ge -1.15216) = 0.0643(0.5 - 0.4357) > \alpha = 0.05$$

(3) Because the value of probability *P* = .0643 is greater than α=0.05, the null hypothesis is not rejected. Thus, at most, 8000 EOH combust basket running is necessary to require replacement and

maintenance, or an overhaul will occur.

The 8000EOH published by the manufacturer will not reject the null hypothesis. However, the value of probability *P* = .0643 is much smaller than the value of probability *P* = .4996 calculated from the estimated 7323 EOH. Therefore, this value, obtained from the Weibull distribution-moment method, is more reliable than the value of the manufacturer.

4.2 Actual Average Failure Time Calculation of the GT21, GT22 and GT23 Gas Turbine Generators of Tai Tam Thermal Power Plant

In the second example, the GT21, GT22 and GT23 gas turbine generators are used to calculate their MTBF in terms of the Weibull distribution-moment method. Table 7 shows the overhaul data recorded for the GT21, GT22 and GT23 from the ignition date (the date that new units began to run) to the present. The data was recorded from the first installation date of 16 September 2005 to the latest dismantling date of 15 December 2010. The result is obtained as follows:

Table 7. GT21, GT22 and GT23 thermal unit overhaul records

Item	Unit	Set Number	Installing Date	Dismantling Date	Number of days	Installing EOH	Dismantlin g EOH	The Interval EOH
1	GT21	004:12	20050916	20070815	698	0.00	8399.00	8399.00
2	GT21	010:12	20070901	20081015	410	0.00	5929.00	5929.00
3	GT21	006:12	20081101	20091015	348	8894.60	13492.00	4597.40
4	GT21	009:12	20091101	20101215	409	5041.90	12395.90	7354.00
5	GT21	003:12	20110101	20120301	425	12843.60	20483.60	8000.00
6	GT22	005:12	20050916	20071015	759	0.00	9606.20	9606.20
7	GT22	011:12	20071101	20081015	349	0.00	4877.80	4877.80
8	GT22	005:12	20081101	20091015	348	9606.20	13767.20	4161.00
9	GT22	007:11;012:1	20091101	20101215	409	4144.71	11808.80	7664.09
10	GT22	005:12	20110101	20120301	425	13767.20	21767.20	8000.00
11	GT23	006:12	20050916	20071015	759	0.00	8894.60	8894.60
12	GT23	002:12	20071101	20081015	349	7524.10	12305.50	4781.40
13	GT23	003:12	20081101	20091015	348	7933.10	12483.60	4550.50
14	GT23	001:1;008:11	20091101	20101015	409	4719.91	12663.80	7943.89
15	GT23	006:12	20110101	20120301	425	13492.00	21492.00	8000.00

Note. Thermal units department of a power plant in Tai Tam, Taiwan.

(1) Mean failure hours: $\overline{T}=\sum_{i=1}^{n} T_i / n = 6850.59$.

(2) Standard deviation: $S=\sqrt{(\sum_{i=1}^{n}(T-\overline{T})^2/(n-1)}$ =1829.653.

(3) Coefficient of variation: $CV = S/T = \sqrt{(\Gamma(1+2/\beta)/\Gamma(1+1/\beta))-1}$ = 0.6708.

(4) According to Table 2, the shape parameter is obtained as $\overline{\beta}$ =3.11.

(5) Scale parameter: $\overline{\alpha}=(1/n)\sum_{i=1}^{n} Ti^{\overline{\beta}}$ =1030725971120.08.

(6) $\overline{\Gamma}=\overline{\alpha}^{\frac{1}{\overline{\beta}}}$ =7290.33.

According to Table 3, $\Gamma(1+1/\beta)$=0.89, MTBF=$\overline{\alpha}^{\frac{1}{\overline{\beta}}\Gamma(1+\bullet 1/\beta)}$ = 7290.33*0.89 = 6488.39. Therefore, the GT21, GT22 and GT23 gas turbine generators need to be maintained after running at most for 6488.39 EOH. The unit overhaul date is similar to the regular maintenance performed on a car. The units must be shut down for maintenance after operating between 8000 EOH and 16000 EOH to replace the thermal components. Although the operation-to-replacement hours of the units are known, the actual running time is unknown. Accordingly, the proportion method is used to estimate the future overhaul date. In the present study, we use the proportional interval of the latest record date to ignition date to estimate the projections.

Table 8 shows the interval EOH of unit GT21 from the ignition date to the latest record date. The EOH of 16 May 2005 (ignition date) is 0, and the EOH of latest overhaul date (1 March 2012) is 34279.4. Thus, the interval EOH is obtained from 34279.4 - 0=34279.4. According to Equation (17),

$$D_{2(GT21)} = EOH_2 * D_1 / EOH_1 = [(2012/03/01)\text{-}(2005/09/16)] * 6488.39/34279.4 = 433.45(days)$$

Table 8. The interval EOH of GT21 unit from the start fired date to the latest record date

Items	Ovehaul Date	Cumulated EOH of Unit Overhaul	Last Unit Overhaul EOH	Interval EOH
1	20050916	0	0	0
2	20120301	34279.4	0	34279.4

Table 9 shows the interval EOH of unit GT22 from the ignition date to the latest recorded date. The EOH of 16 September 2005 (ignition date) is 0, and the EOH of the latest overhaul date (1 March 2012) is 34309.09. Therefore, the interval EOH is obtained from 34309.09 - 0=34279.4. According to Equation (17),

$$D_{2(GT22)} = EOH_2 * D_1 / EOH_1 = [(2012/03/01)\text{-}(2005/09/16)] * 6488.39/34309.09 = 433.0751(days)$$

Table 9. The interval EOH of GT22 unit from the start fired date to the latest record date

Items	Ovehaul Date	Cumulated EOH of Unit Overhaul	Last Unit Overhaul EOH	Interval EOH
1	20050916	0	0	0
2	20120301	34309.09	0	34309.09

Table 10 shows the interval EOH of unit GT23 from the ignition date to the latest recorded date. The EOH of 16 September 2005 (ignition date) is 0, and the EOH of the latest overhaul date (1 March 2012) is 34279.39. Therefore, the interval EOH is obtained from 34279.39 - 0=34279.39. According to Equation (17),

$$D_{2(GT23)} = EOH_2 * D_1 / EOH_1 = [(2012/03/01)\text{-}(2005/09/16)] * 6488.39/34279.4 = 434.833(days)$$

Table 10. The interval EOH of GT23 unit from the start fired date to the latest record date

Items	Ovehaul Date	Cumulated EOH of Unit Overhaul	Last Unit Overhaul EOH	Interval EOH
1	20050916	0	0	0
2	20120301	34279.39	0	34279.39

The days can be calculated in terms of the average method, because the thermal component is installed in three separate units. Thus, the result is obtained as follows. If calculated on an annual basis, $Years = 434/365 = 1.19 years$, then the period of overhaul is approximately 1.19 years.

$$D_{2(GT23)} = (D_2(_{GT21}) + D_2(_{GT22}) + D_2(_{GT23}))/3 = (433.45 + 433.0751 + 433.833)/3 = 433.786(days)$$

In this section, two hypotheses will test if the value of EOH obtained from the Weibull distribution is more accurate than the value of EOH published by the manufacturer. First, confidence interval testing is performed to determine if the value of 6488.39 EOH obtained from this study and the value of 8000 EOH provided by the manufacturer fall within the confidence interval. Next, hypothetical testing is performed using the values falling inside the confidence interval.

Confidence interval testing. In this case, a 95% confidence level was set, and the confidence intervals were obtained as follows:

(1) $\overline{X} \pm t_{n-1,\alpha/2} s/\sqrt{n} = 6850.59 \pm 1.96 * 1829.653/\sqrt{15} = 6850.59 \pm 925.9322$.

(2) $5924.658 \le u \le 7776.522$.

According to these evaluations, the value of 6488.39 EOH obtained from this study falls inside the confidence interval, but the value of 8000EOH provided by the manufacturer falls outside the interval.

Hypothesis testing. The value of 8000 EOH provided by the manufacturer falls outside the interval, and therefore, only the value of 6488.39 EOH obtained from the study is verified.

(1) $\overline{X}(Mean) = 6850.59$, $S(Sandard) = 1829.653$, $n(Sample\ Size) = 15$.

The $\overline{X} = 6850.59$ is greater than the estimated value of 6488.39, so it is assumed that the combust basket running at most 6488.39 EOH must be replaced and maintained, or an overhaul occurs.In this section, hypothetical testing shows whether the value 6488.39 EOH is correct or not. First, it is assumed that the combust basket running at most for 6488.39 EOH must be replaced and maintained, or an overhaul will occur.

(2) H_0: u<=6488.39, H_1: u>6488.39.

(3) Then the value of probability P is calculated. The alternative hypothesis symbols is '>', so the right-tailed test is adopted.

$$P(\overline{X} \geq \overline{X}^* \mid u = 6488.39) = P((\overline{X} - 6488.39)/(1829.653/\sqrt{15}) \geq (6850.29 - 6488.39)/(1829.653/\sqrt{15})) \quad (4)$$
$$= P(Z \geq 0.7667) = 0.1949(0.5 - 0.3051) > \alpha = 0.05$$

Because the value of probability P = .1949 is greater than the α value of 0.05, the null hypothesis is not rejected. Therefore, the combust basket running at 6488.39 EOH must be replaced and maintained, or an overhaul will occur.

(5) The value of 8000 EOH from the manufacturer, which falls outside the interval, is less reliable than the estimated value of 6488.39 EOH.

4.3 Program to Assist the Next Scheduled Forecast

As shown in the previous examples, the EOH of MTBF obtained using the Weibull distribution-moment method is the core of this study. In addition, four important factors affect the future schedule of thermal components: the next overhaul-date factor, the requisitions-timing factor, the inventory-timing factor, and the regeneration-timing factor. The present study develops a decision support system to assist the forecasting of the overhaul date using these conditions. This system will automatically predict the future schedule and inventory of the components, according to two parameters (unit overhaul date and MTBF) obtained from the Weibull distribution-moment method. First, as shown in Fig. 10, the value of 7323.37 is entered into the repair interval EOH field, and the date of 2003/05/02 is entered into the ignition date field.

Second, the forecasted scheduling parameters are inputted, as shown in Fig. 11. Then the component needs for the combustor basket (thermal component is encoded as No. 33000001) during the period 2010 to 2020 are estimated. The thermal component ID of the unit is selected, and the estimated interval of each overhaul is entered. Next, [OK] is selected to show the result of component needs during the estimated period. Additionally, the failure of EOH is calculated. Fig. 12 shows the forecasting schedules of the thermal component. Fig. 13 shows the estimated day on which the combustor basket thermal components will be dismantled during the period of 2012 to 2020. Fig. 14 shows the predicted date of regeneration and its completion for combustor basket thermal components.

Fig. 10. The unit information-management system

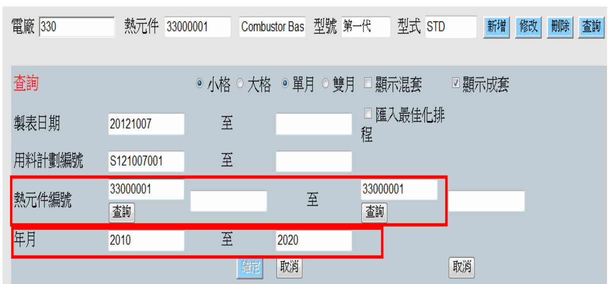

Fig. 11. Forecasted scheduling parameters

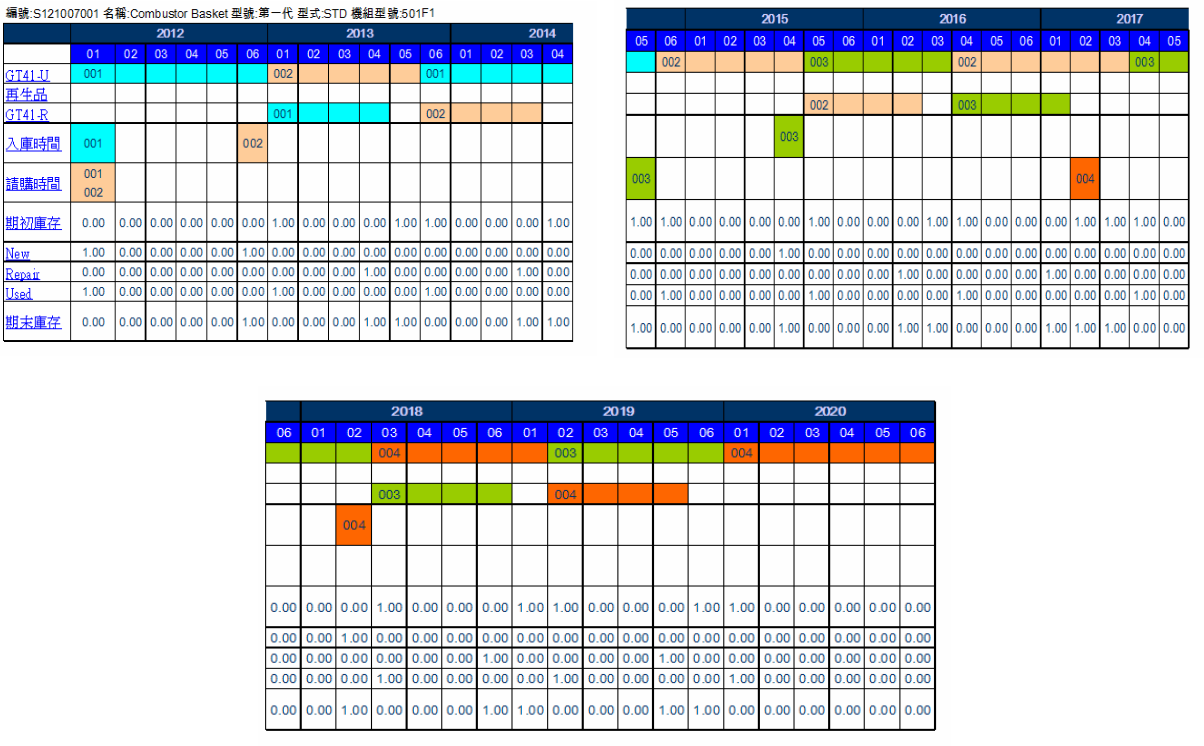

Fig. 12. The predicted schedule of thermal component

01	001	001:16	20120209	20130209	
02	002	002:16	20130209	20131227	
03	001	001:16	20131227	20141113	
04	002	002:16	20141113	20150930	
05	003	003:16	20150930	20160816	
06	002	002:16	20160816	20170703	
07	003	003:16	20170703	20180520	
08	004	004:16	20180520	20190406	
09	003	003:16	20190406	20200221	
10	004	004:16	20200221	20211124	

Fig. 13. The forecasted days of thermal component dismantlement

項次	套號	內容	起用日	結束日	顯示顏色
01	001	001:16	20130209	20130808	
02	002	002:16	20131227	20140625	
03	002	002:16	20150930	20160328	
04	003	003:16	20160816	20170212	
05	003	003:16	20180520	20181116	
06	004	004:16	20190406	20191003	

Fig. 14. The predicted period of thermal component regeneration

According to Fig. 12, the ignition date is 9 February 2013. On 13 November 2014, the GT41 unit is estimated to run 7323.37 EOH, and needs to be overhauled and maintained. At this dismantled time, the thermal component will be regenerated and maintained for the first time. Set 001 was reintegrated into the inventory as early as 13 August 2013, and can be reinstalled. Fig. 13 shows that Set 001 will exceed the service life on the overhaul date of 23 November 2014. Thereafter, it cannot be regenerated. Set 002 is reintegrated into the inventory on 25 June 2014, so the unit can be charged with Set 002. If the unit runs for 7323.37 EOH until the overhaul date of 30 September 2015, Set 002 will be sent to the maintenance plant for its second regeneration. Until that time, the power plant will not have any thermal components in the inventory, so it is necessary to procure a new set of components (Set 003). According to the principle of 2 years for requisitions, it will be necessary to order a new component (Set 003) before 3 September 2014 to ensure that it will be ready for use on the overhaul date of 30 September 2015. Therefore, 10 or 20 years of schedule forecasting are obtained through the decisions support systems built in this study.

5 Conclusions

Information about thermal elements is vital for the functional operation and planning of a power plant. However, the typical method of schedule component planning is based on the data provided by the manufacturer, or the experience of the power plant staff. Various usages and environments can also affect the service life of thermal elements. Ignoring these external factors may lead to wasting resources and depleted inventory problems. Therefore, the average interval between each malfunction occurrence in this study will facilitate decision making regarding the inventory level and procurement timing of the thermal components for a gas turbine generator. The goal is to make the demand and supply of the thermal components transparent and reduce the chance of the power plant shutting down because of insufficient inventory. Excess inventory can also be avoided. The proposed method will assist the power plant with planning optimal procurement schedules for thermal components. The most accurate procurement date and the most economical procurement quantity of thermal component can be obtained to reduce the overall costs of maintenance for thermal components.

In addition, some absolute principles must be considered for the use of thermal components, such as the time of regeneration, the period of regeneration, service life, and requisitions timing. And, these principles can be paired with the estimated overhaul date to build a decision analysis system for determining gas turbine engine components needs, to facilitate the estimation of procurement of thermal components, improving the accuracy of procurement prediction, and reducing the inventory costs of the thermal elements.

In the future, the proposed system can also be used to improve the reliability of some other critical components, such as the rotors and the stators of the turbine engine power generator. For further cost reduction of inventory components, MTTF (Mean Time To Failure) and MTTR (Mean Time To Restoration) can be considered to apply in the system.

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