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Gas turbine maintenance optimizing using the reliability-centered maintenance method

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Abstract

Gas Turbine is one of the important equipment in the production process in the oil and gas industry. This equipment is used as the prime mover of the compressor to the gas supply. The company has implemented preventive maintenance and condition monitoring in the context of gas turbine maintenance as well as scheduled shutdown every 52,000 hours of operation time. Along with efforts to increase production, the company's management policy has implemented a gas turbine maintenance efficiency program from 52,000 hours to 72,000 hours of operation. This policy is based on the consideration that productivity decreases over time and component replacement during Major Inspection (MI) and Hot Gas Path inspection (HGPI). This policy will certainly have an impact on the reliability, performance, and failure rate that will be experienced by gas turbines as well as their impact on maintenance costs. This study aims to recommend optimal maintenance strategies for gas turbines using the Reliability Centered Maintenance (RCM) method related to availability, reliability, maintainability, and maintenance costs. In this study, an analysis of the causes and effects of failure was carried out using the Failure Mode and Effect Analysis (FMEA) method, with the parameters of failure frequency and consequences of failure then analyzed using the RCM worksheet to determine an effective maintenance strategy. The results of this study obtained maintenance strategy for Gas Turbine components which are Failure finding, Redesign on conditioning, and Schedule discard task. The components that are scheduled for repairs are compressors and turbines and components that receive a component replacement schedule are Air Inlet and Combustion. The application of the RCM method has been able to reduce maintenance costs by up to 30.678% along with reduced downtime rates, decreased failure rates and the number of Mean Time To Repair (MTTR) hours.

Keywords:
Gas Turbin, RCM, FMEA, Failure Finding, Maintenance schedule.

1 Introduction

Maintenance aims to maintain the performance of an equipment or component in accordance with its functional standards and prevent unwanted things from happening, such as malfunction and failure that is too fast for all industrial equipment, both operating and functioning as spare parts [1], [2], [3].

Failure that occurs is usually caused due wear out as an effect of continuous operating loads, and also due to wrong operating steps. Maintenance of gas turbines always depends on operational factors with different conditions in each area, because gas turbine operations are highly dependent on operational area conditions. All gas turbine manufacturers have established a safe setting in operation so that the turbine is always within safe conditions and on time to carry out routine maintenance.

In operating the gas turbine, the company has carried out a maintenance strategy by combining Preventive Maintenance (PM) and Predictive Maintenance (PdM) or Condition Monitoring (CM) methods. The problem faced is that the results of the implementation of the maintenance strategy have not been optimal yet. The availability of complex systems, such as gas turbines, is highly related to parts reliability and maintenance policies [4]. The policy has influence not only on the repair time side, but also on the systems reliability side which affects system degradation and availability [5], [6], [7] [8], [9].

For the efficiency program, the company's management policy proposes an overhaul period from 52,000 to 72,000 hours. This consideration is based on inspection data and MI and HGPI reports from 1989 to 2014. In line with this policy, it is necessary to conduct a study related to the reliability of equipment, failures, and critical components in gas turbines, where the overhaul schedule is extended to 2.3 years (27 months) or 20,000 working hours.

RCM is a method used to determine what must be done to ensure that each physical asset continues to work as desired or a process for determining effective maintenance by combining practices and strategies from preventive maintenance and corrective maintenance to maximize service life and equipment functions at minimal cost [5], [6], [10].

Failure mode and effect analysis (FMEA) is used to determine the mode and effect of failure experienced by each component [11], [12], [13]. FMEA discusses the various types of failures that occur, the causes of failure, and the effect of failure caused by each component. Determination of the preventive maintenance schedule is obtained by calculating the MTTR and Mean Time to Fail (MTTF) using the Weibull distributions [13]. The result of implementing RCM is in the form of applicative and effective maintenace recommendations.

The purpose of this study is to recommend an optimal maintenance strategy for gas turbines using the RCM method in line with the company's policy of implementing an overhaul schedule from 52,000 to 72,000 hours.

1.1 Gas turbine maintenance

Gas turbines are equipment that greatly affects the company's life cycle, so it is necessary to improve complex system maintenance policies and aim to reduce failures due to unexpected events on critical components. maintenance of gas turbine components is not only carried out when carrying out an overhaul but also requires early detection through several important parameter inspections and monitoring [14].

For this reason, it is necessary to obtain better maintenance activity intervals, through the application of the Reliability Centered Maintenance (RCM) method. This method is the development of a method that has been implemented in the company so as to achieve the optimization of the gas turbine maintenance system with the gas turbine data study variables at the Major Inspection (MI) of the main components.

The performance of gas turbines in the combustion chamber area that works under extreme conditions will greatly affect the life cycle and maintenance costs [7]. Development of a gas turbine maintenance management program for sections (combustion chamber, transition piece, turbine 1st), as an optimation of turbine maintenance programs that support additional functions such as optimation of maintenance schedules, modification of operational schedules, and opinions from management according to maintenance history records.

The probability of failure of a machine is the inverse of its probability of reliability as shown in eq. (1), where: R(t) is Reliability and Pf(t) is Probability of failure of the time function.

$$Pf(t)=1-R(t) \tag{1}$$

1.2 Reliability Centered Maintenance

Maintenance is an activity carried out so that components or equipment can be run according to their original performance standards. Also defined as an action required achieving a result that can restore or maintain equipment in a condition that is always functioning. The purpose of maintenance is to maintain the age life of the equipment, ensure the optimal level of availability of production facilities, ensure the operational readiness of all facilities for emergency use, and ensure the safety of operators and users of facilities.

RCM is maintenance management that can be classified into a planned preventive maintenance system [15]. RCM is defined as a process that is used to determine what should be done to guarantee that each physical item or system can run properly according to the function desired by the user. [5], [16]. RCM directs the handling of items so that they remain reliable in performing their functions while still referring to the effectiveness of maintenance costs. RCM combines two types of maintenance actions, namely preventive maintenance and predictive maintenance.

RCM focuses more on the use of qualitative analysis for components that can cause failure in a system. The seven questions are outlined in the form of a failure mode and effect analysis (FMEA).

Reliability can be defined as the probability with a certain level of confidence that a component, product, or system will perform its function as designed without failure/damage at a certain age for a particular purpose and environment.

Optimation means being able to meet requests received with due regard to minimizing the costs required. This activity also means maintaining the reliability of each facility or production process as a whole. In order to perform its functions properly, the maintenance system must have a good response to damage that will arise as well as adequate work capacity to deal with the damage that has occurred [17].

The maintenance system aims to expedite the operation of the production process so as to achieve economic savings. By considering the decision variables that are made, the short-term maintenance policy will later be in the form of a combination of corrective and preventive maintenance. This phenomenon will be shown in Fig 1. Cost criteria for maintenance.

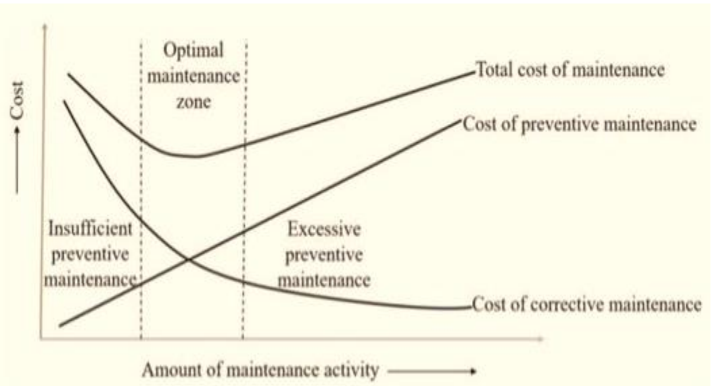

Fig 1. Maintenance cost criteria

1.3 Failure Rate

The failure rate is the number of failures per unit of time. The failure rate can be expressed as a comparison between the number of failures that occur during a certain time interval with the total operating time of a component or system. The failure rate can be expressed by eq. (2), where $\lambda(t)$ is Failure rate, f(t) is The number of failures during operating period and T is Total operating time.

$$\lambda(t) = f(t)/T \tag{2}$$

1.4 MTTF

Mean time to failure (MTTF) is defined as the average failure time of a component that has a failure density function. Mathematically it can be explained by the following eq.(3):

$$MTTF = E(T) = \int_0^\infty R(t)\,dt \tag{3}$$

1.5 Weibull Distribution

The Weibull distribution is one of the distributions that is often used, especially in the field of reliability and statistics because this distribution has the ability to approach various types of data distribution. The Weibull distribution provides accurate failure analysis and very small sample risk prediction using a simple and useful graphic plot [18][19].

The Weibull distribution has two parameters, which are β (shape parameter) and η (scale parameter) so the probability density function (PDF) is expressed as follows eq.(4):

$$f(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \exp[-(\frac{t}{\eta})^{\beta}] \tag{4}$$

The realibility function is eq. (5):

$$R(t)= \int_t^\infty f(t)dt = \exp\left[-(\frac{t}{\eta})^{\beta}\right] \tag{5}$$

The failure rate is eq. (6):

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \tag{6}$$

If β<1, then there is a decrease in the failure rate, β = 1 constant failure rate, and β> 1, then there is an increase in the failure rate.

Mean time to failure (MTTF) is the average time a component fails eq. (7).

$$MTTF = \eta\, \Gamma\left(1+\frac{1}{\beta}\right) \tag{7}$$

The Weibull distribution has three parameters, the parameters are β (Shape Parameter), η (Scale Parameter), and γ (Location Parameter). The location parameter represents the failure-free or initial period of item usage.

The probability density function of the three-parameter Weibull distribution can be expressed eq. (8).

$$f(t) = \frac{\beta}{\eta}\left[\frac{t-\gamma}{\eta}\right]^{\beta-1} exp\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right] \tag{8}$$

The Mean Time between Failure (MTBF) of the three-parameter Weibull distribution can be expressed as feq. (9):

$$MTTF = \gamma + \eta\left(1+\frac{1}{\beta}\right) \tag{9}$$

1.6 Availability

Availability is defined as the probability that an item is available when needed, or the proportion of the total time an item is available for use. Therefore Availability is a function of the failure rate. The availability of a system can be expressed in a mathematical eq.(10):

$$A = MTTF/(MTTF + MTTR) \tag{10}$$

1.7 Maintainability

Maintainability is the probability that a component or system that has failed will be repaired to a specified condition within a certain period of time when maintenance is performing according to a specified procedure. In reliability, focused on designing a device without failure as long as possible. Meanwhile, maintainability focuses on designing equipment so that a failure can be repaired as quickly as possible. Maintainability for the Weibull distribution can be expressed in the following eq.(11):

$$M(t) = 1 - exp[-(\lambda t)] \quad (11)$$

Maintainability for the Weibull distribution can be expressed in the following eq. (12)

$$M(t) = 1 - exp\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right] \quad (12)$$

One of the weaknesses in Reliability Centered Maintenance is the lack of model optimization to determine optimal maintenance intervals. It is formulated that the total maintenance cost is the cumulative sum of failure costs and maintenance costs, so it can be calculated by eq.(13), where TC is Cost Total, C_M is Maintenance costs, C_R is Repairing cost, S is Optimal maintenance time interval, and β amd η is the Weibull distributions parameter of the breakdown time interval.

$$TC = \frac{(S^{\beta}.C_R) + (\eta^{\beta}.C_M)}{(\eta^{\beta}.S)} \quad (13)$$

2 Research method

The research method begins with analyzing gas turbine maintenance history data which consists of data on the replacement of critical components in gas turbines during major inspections and Hot Gas Path inspections from 1995 to 2008. Then the RCM method is applied to obtain optimal maintenance policy recommendations. The stages of this research are shown in Fig 2.

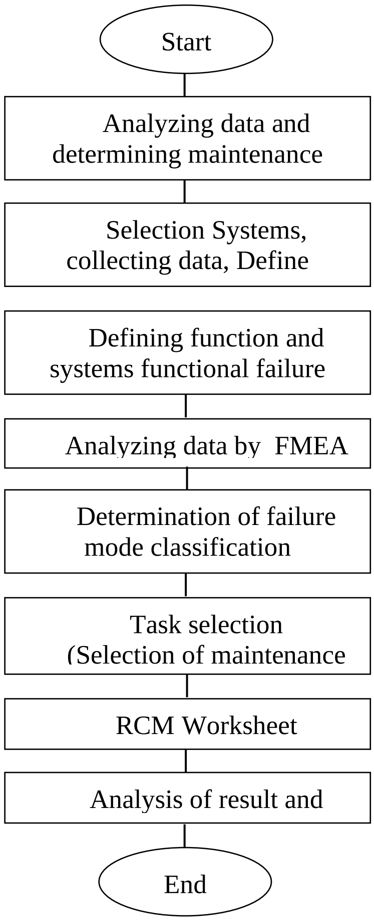

Fig 2. Research stages flowchart

Stages of research carried out with the following steps:

1. Determination of maintenance intervals and maintenance costs which are including:
   a) MTTF and MTTR.
   b) Availability and maintainability
   c) Cost of failure and cost of maintenance
   d) Maintenance interval
2. The function and scope of the gas turbine study under review consist of the following components:
   a) Air Inlet
   b) Axial flow compresor
   c) Combustion system
   d) Turbin section
3. This stage describes functions related to speed, output, capacity, and equipment performance issues. While functional failure can be interpreted as the inability of equipment to fulfill its function at a standard performance that can be accepted by the user. A function can have one or more functional failures.
4. At this stage, the causes, mode, and impact of component failure will be analyzed as well as the calculation of the RPN value for recommendations for actions that must be taken related to what maintenance policies will be carried out to anticipate, prevent, detect, or repair them.
5. This stage is a qualitative measure to classify failure modes. The failure modes can then be classified into 4 categories.
6. Task Selection is performed to determine effective strategies and select the most efficient task for each failure mode.
7. At this stage, the data is analyzed in the form of an RCM worksheet which integrates the results of the FMEA, resulting in recommendations for maintenance strategies.
8. This last stage is a discussion of the results of the application of the RCM method related to the application of efficiency policies from the company's management which implements an overhaul period from 52,000 to 72,000 hours.

3 Result and discussion

The gas turbine work system operates for 24 hours per day with a specified operational target (52,000 hours of operation) for six years and during the implementation of the HGPI in the three years of operation, which is 26,000 hours. In accordance with the agreed planning, the MI schedule will be held for 72,000 hours. The inspection process for all gas turbine components is recorded within 24 hours using a computer system.

3.1 Determination of time interval data distribution

Data on downtime during operations from (2002–2008) was obtained based on trip events caused by rising temperatures, overspeed, control system instruments, and vibration which causes failure. Data on the time for replacing critical components is carried out based on the results of inspections and maintenance according to the schedule carried out at the major inspection.

Determining the distribution of failure time interval data using Minitab version 15, obtained downtime data as shown in Table 1. shows downtime data during gas turbine operations from 2002-2008, it can be seen that the trip trend has decreased. Failure data for each component in the gas turbine β = 0.7477

Table 1. Distribution of failure time intervals

NO	Years	Failure (Hours)			Total	Operation Time(Hours)
		HGPI	MI	DOWN TIME		
1	2002	-	-	-	0	8760
2	2003	-	-	-	0	8760
3	2004	547	-	-	547	8213
4	2005	-	-	10	10	8750
5	2006	-	-	-	0	8760
6	2007	-	-	2,05	2,05	8757
7	2008	-	648	13,28	661,28	8098,7
Total		547	648	25,33	1220,33	60099,7

3.2 Determination of MTTF and MTTR

The distribution of failure times is the distribution of system frequencies for the length of time a product lives. The failure rate of a product is the probability that a product will be repaired, which is the average number of products or systems that fail per unit of time.

The mean time between failures as the average time the system will operate until the next failure occurs can be measured by the ratio between the total observation time and the average number of failures found.

By using Minitab 15 software, the data to determine the mean time to failure of the turbine obtained MTTF 9489.3, MTTR 0.3668, MTBF 9489.667, availability 0.999961, maintainability 1, reliability 0.998437964, probability of failure 0.00156.

Based on the MTTF value of 9489 hours, the gas turbine will experience the first damage after operating for 9489 hours with an error rate of 5% (95% confidence interval). Meanwhile, gas turbines that can operate more than 36,000 hours are around 4.534%.

The probability plot graph informs the analysis of results based on the Weibull distribution obtained reliability when the operating time of the gas turbine exceeds 35100 hours, then the reliability will decrease to 4.8045% and the failure rate is 0.0000647.

3.3 System Function Analysis and Functional Failure

The gas turbine according to its function which consists of several main components has worked based on the time set by the company. The company carried out maintenance according to its function within a period of MI 60100 hours or from 2002 to 2008 and carried out inspections of the main components of the gas turbine. Each component has performed a specific function in terms of the main function. Failure in a component greatly affects the entire system and will result in a decrease in turbine operation such as the nominal power that has been set according to the turbine operation manual issued by the manufacturer. The critical level of gas turbine equipment is caused by: Safety factors, Production, Spare part availability and Direct Maintenance Costs.

3.4 Failure Mode Effect and Analysis

FMEA is a technique that is widely used to assess the causes and effects of damage to the overall system reliability. The function column shows the function that the component has, the potential failure mode column shows the cause of the failure, and the potential effect of failure shows what happens if the component fails to meet its performance standards. The potential causes column shows the mechanism of the failure, and the current process/design controls column shows how to handle it and the actions taken, as well as weighting severity, occurrence, and detection for each component, then calculating and sorting based on the Risk Priority Number (RPN).

Table 2 shows the results of calculating the RPN values for the five components of the gas turbine.

Table 2. RPN value

No	Komponen	S	O	D	RPN
1	Compressor Rotor	8	4	5	160
2	Combustion	9	4	4	144
3	Air Inlet	6	4	4	96
4	Compressor Stator	7	4	3	84
5	Turbine section	8	3	3	72

Table 2 explains that the compressor rotor is the component that has the highest RPN value of 160 and the lowest is 72, namely the turbine section component. The highest RPN value indicates the lowest system reliability and is a priority component for maintenance action. This value will later be used as a guide to finding out the most serious problems with indications that require priority serious maintenance.

3.5 Data on Failure Time of Critical Parts Components

Based on the provisions of the critical component at a time interval of 8000 hours is the combustion liner. In addition to the standards that have been set, the company also takes into account the downtime that occurs and takes precautions against components with the coating process in order to increase the age life of these components.

Data from MI's report on components replaced for gas turbines is shown in Table 3. Components such as inlet guide vanes, fuel nozzle tips, transition pieces, and second-stage nozzles were not replaced but only checked and cleaned, and reassembled.

Table 3. Main Components replaced during MI.

Components	Gas Turbin		
	1995	2001	2008
Comb liner	2	4	4
Cross fire tube	12	7	6
Retrainer	10	10	12
First stage nozzle	1	1	1
Rotor HP/LP	1	1	1
Bearing	2	2	4

3.6 RCM Worksheet

RCM focuses more on the use of qualitative analysis for components that can cause failure in a system analyzed with FMEA and RCM II decision diagram worksheets. The result of the RCM explains that the types of failure consequences of gas turbines are hidden failure, safety, and environment, and operational and non-operational consequences. The proposed task that is expected for the company for each gas turbine equipment is scheduled on condition task and failure finding. For the compressor, combustion, and turbine, a redesign is also carried out on conditioning, scheduled discard tasks, and scheduled restoration tasks.

In principle, the schedule on condition task maintenance activity is predicting failure, and then the corrective maintenance step is implemented after the failure mode that occurs is known.

3.7 Determination of Optimal Maintenance Costs and Maintenance Intervals

One of the objectives of maintenance is to ensure the optimum availability of equipment installed for production or service in order to obtain the maximum possible return on investment. The total maintenance cost is the cumulative sum of failure costs and maintenance costs, resulting in a cost reduction of 30.678%.

Furthermore, the cost of gas turbine downtime per year is calculated at $ 24.95, with a repair time of 273 hours, a gas turbine working time of 8585,714 hours, and an hourly operator work fee of $ 8.8.

3.8 FMEA Analysis

Based on the FMEA results, each component has a different failure mode from one other. Air inlet as a channel for air to enter the compressor and serves to filter dirt and dust carried in the air. Based on the FMEA analysis in the RCM method, this concept can be used to recommend the task of selecting components that have a critical value greater than component failure.

Component failure can cause a significant reduction in gas turbine performance. Gas turbine inspections will be analyzed in full with system monitoring based on temperature, pressure, and vibration measurements. The data can be used to determine equipment trends and limit values to be determined as indicators of potential failures.

The identification results can provide information for scheduling maintenance tasks before functional failures occur. Data analysis based on predictive maintenance implementation policies recommended by RCM. Most of the critical components in a gas turbine can be determined by carrying out predictive maintenance or preventive maintenance. The function failure that occurs in the inlet air is caused by a dirty filter which prevents air from entering the turbine and can result in a decrease in efficiency.

In the compressor rotor failure mode is caused by the entry of particles with air into the gas turbine so that they can increase the temperature and erosion of the blades and cracks which can cause deformation, can cause high vibrations so that it is necessary to shutdown.

In the compressor stator, there is a loss of performance and efficiency caused by centrifugal force so that the blades become eroded resulting in fracture.

In combustion, there is erosion of the thermal coating, thermal erosion of the nozzle and hotspots in the combustion chamber so that high temperatures have an impact on leaky gasket seals which can reduce turbine performance.

To determine the critical component the researcher detected that no maintenance system could show the evolution of a failure mode. The steps to mitigate the possibility of a component failure are:

1. The amount of pressure and temperature in the combustion chamber is monitored directly and the diagnosis of the combustion process can result in the condition of the turbine burning quickly.
2. The sliding system on the radial and thrust bearings can affect the lubricating oil pressure and temperature within the specified limits. Oil can be analyzed periodically to detect metal particles contained in the oil fluid. Based on the time and volume as well as the particles and the chemical composition of the oil can be used as an indicator of the degradation of the bearing material.
3. Monitoring of thrust bearings for axial vibration. These bearings can direct the axial vibrations that occur, and these bearings can be used to mark potential failures that occur in sliding. Bearings can also provide further information about the rotating shaft in a gas turbine as a basis for planning preventive and predictive maintenance.
4. The air filtration system is installed at the inlet and the lubricating oil circuit is monitored with a differential pressure gauge. Any increase in pressure can be used as an indication of the presence of particles in the air filter. It is recommended to clean the filter of particles; this can give an indication of a decrease in gas turbine performance.

The RPN value obtained from FMEA, Compressor has the highest average RPN value of 160, then Combustion is followed by 144, Air inlet 96, and Turbine sections 72. The largest RPN value which is compressor has indicated that this equipment in the gas turbine system is ranked first where this equipment really needs maintenance. The failure rate on Compressor is 0.0421, combustion is 0.0233, the air inlet is 0.0057, and the turbine sections are 0.0023.

3.9 Analisa RCM

The types of failure consequences of gas turbines are a hidden failure, safety, environment, and operational and non-operational consequences. The proposed tasks expected for gas turbine companies are Scheduled on condition task and failure finding. For the compressor, combustion, and turbine, a redesign was also carried out on conditioning, scheduled discard tasks, and scheduled restoration tasks.

In principle, the schedule on condition task maintenance activity is predicting failure, and then takes a corrective step after the failure mode that occurs is known.

3.10 Weibull Distribution Analysis

Results from analysis of Weibull distribution data on gas turbines using Minitab v.15 software. β, η, and MTTF values were obtained as shown in Fig 3. After obtaining the data distribution, then determine the MTTF and MTTR. It is known that the most frequently damaged equipment is the gas turbine which has an average time between failures of 9489. The average value of the time between failures for this gas turbine is low due to the workload on the turbine.

Based on the MTTF value of 9489, the gas turbine will experience the first damage after operating for 9489 hours with an error rate of 5% and a confidence interval of 95%. Gas turbines can operate beyond 36000 hours with a 4.5% breakdown. Analysis of the results based on the Weibull distribution obtained reliability when the operating time of the gas turbine exceeds 35100 hours, then the reliability will decrease to 4.8045% and the failure rate is 0.0000647.

The distribution value at the operational time has a shape parameter value (β) less than 1 ($\beta < 1$), which means that the gas turbine equipment has decreased the failure rate (infant mortality).

The characteristic of life (η) is showing age with a 63.2% possibility of failed components. Characteristic life (η) = 7950.09 means that components aged 7950.09 hours are likely to fail by 63.2%.

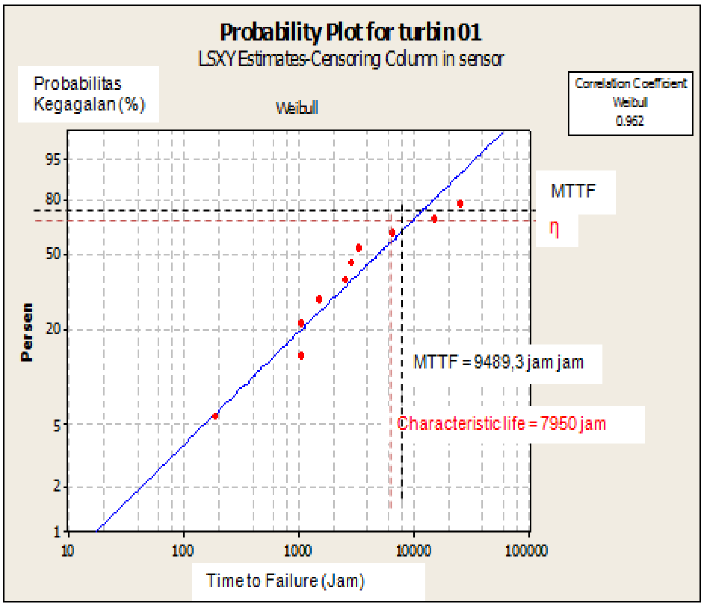

Fig 3. Weibull Data Plot of Gas Turbine

3.11 Determination of optimal maintenance costs and maintenance intervals

One of the objectives of maintenance is to ensure the optimum availability of equipment installed for production or services in order to get the maximum possible return on investment. The total maintenance cost is the cumulative sum of failure costs and maintenance costs as shown in Fig 4.

Fig 4 informs that by applying the RCM method, the total maintenance costs will decrease. this is in line with the increase in MTTR and MTBF as well as decreased downtime.

The tendency of repair costs is increasing every year, therefore it is necessary to upgrade the maintenance system so that the problem of repair costs can be reduced. If maintenance is carried out properly according to predetermined standards, the tendency for maintenance costs to decrease every year.

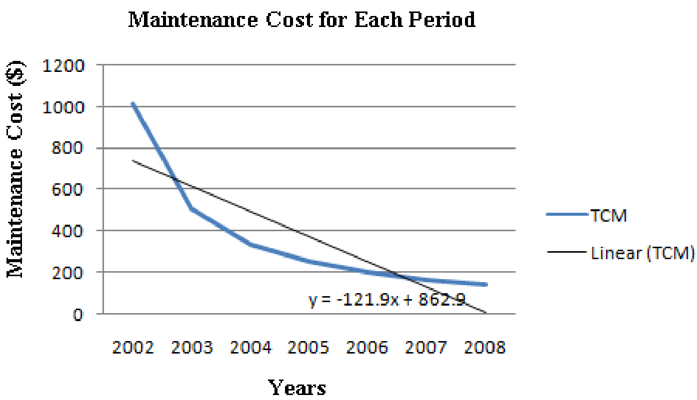

Fig 4. Maintenance costs for each period.

4 Conclusion

Gas Turbine is one of the critical equipment, where if a failure occurs it will result in the cessation of the production process. The MTTF value of the gas turbine is 9.489 hours and the MTBF is 9.490 hours. if the company's management policy wants to implement a maintenance efficiency program from 52,000 to 72,000 hours of operation, then management should consider conducting MI every 9,489 hours of operation, and then continuously every 9,490 hours of operation. while HGPI can be performed in 75,187 hours of operation. As for the components of the gas turbine which are the priority for inspection, maintenance and replacement starting from the highest RPN value, namely Compressor, Combustion, Air inlet 96, and Turbine sections.

The design of maintenance carried out for Gas Turbine components to increase and maintain their reliability includes Failure finding, Redesign on conditioning, Schedule discard task. The components that are scheduled for repairs are compressors and turbines. Components that receive a component replacement schedule are Air Inlet and Combustion. The Failure Finding policy is applied to all equipment by carrying out periodic scheduled preventive maintenance activities.

The application of the RCM method has been able to reduce maintenance costs by up to 30.678% along with reduced downtime rates, decreased failure rates and the number of MTTR hours. Increasing the availability of gas turbines along with optimizing the application of appropriate maintenance methods.

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