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Availability Improvement Methodology in Thermal Power Plant

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Abstract

Availability of a complex system of thermal power plant is strongly influenced by maintenance program and component reliability. Various maintenance techniques, likes RCM (reliability-centred maintenance), RBM (risk based maintenance) and CBM (condition-based maintenance), have been applied to improve the availability. Implementation of RCM, RBM, CBM alone or combined RCM and RBM or RCM and CBM is a maintenance technique used in thermal power plants. This study develops an new maintenance methodology integrating RCM, RBM and CBM to increase the availability of thermal plants. The method generates MPI (Priority Maintenance Index) and FDT (Failure Defense Task). MPI is used to determine the priority of components in maintenance program. FDT consists of the tasks of monitoring and assessment of conditions other than maintenance tasks. Both MPI and FDT obtained from development of functional tree, failure mode effects analysis, fault-tree analysis, and risk analysis (risk assessment and risk evaluation) were then used to develop and implement a plan and schedule maintenance, monitoring and assessment of the condition and ultimately perform availability analysis. The results of this study indicate that the reliability, risks and conditions-based maintenance methods, in an integrated manner can increase the availability of thermal power plant.

Keywords: Integrated Maintenance Techniques, RCM, RBM, CBM, Availability, MPI

1. Introduction

A complex system with high production loss value, such as a power plant, keeping availability and reducing costs related to maintenance are at the top of management concerns in a large enterprise. The system availability is determined the component reliability and the maintenance program implemented. That program influences the repair time and the reliability of component and system. Normally, a system's reliability will deteriorate and this increases the probability of failure. Further, the availability of the system will decrease. In case of the power plant, the unavailability occurred results a high cost of production loss depend on the time duration of shutdown condition.

Availability measures are related to how long time the unit can operate in the certainty period time. Most power plants use the index proposed by IEEE std.762^{tm} (2006) to define availability [1]. That index represents the percentage of a given period of time, expressed in hours that the unit is in service (including reserve shutdown state). Reference [2] defined expressed by the ratio of the mean time to failure to the sum of the mean time to failure plus the mean time to repair. The index, usually evaluated monthly, is reported in a Generating Availability Data System (GADS) and can be used for comparison between different generating systems.

A reduction in availability is caused by planned maintenance and unplanned maintenance actions. Improper maintenance can result a repair time longer than that based on manufacturer's recommendation or the system reliability decreases. For keeping the system availability, a proper maintenance program is needed.

In a complex system, there are several maintenance problems i.e. how to identify critical components, how to priority and how to maintain them. Maintenance techniques developed in the literature propose various rules to category the system components into critical component. Then, they determine the priority maintenance and finally plan a maintenance program which consists of preventive maintenance and condition monitoring tasks.

Various maintenance techniques have been proposed to increase an availability of any systems [3]. Generally, the established maintenance techniques have been developed in the literature i.e. Reliability Centred Maintenance (RCM), Risk Based Maintenance (RBM) and Condition Based Maintenance (CBM).

The development and applying of RCM, RBM and CBM can be found in [4]-[10], [11]-[15] and [16]-[19] respectively. Several researchers have been integrated two of those maintenance techniques in one maintenance program. Integration between RCM and CBM, RCM and RBM has been done in [20] and [21], respectively. This integration increases the availability higher than that each the techniques is implemented separately. In the present, the study of integration of those techniques has been not developed. Integration all techniques are expected to yield the increasing of availability higher than that resulted of integration between RCM – RBM or RCM – CBM.

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Nomenclature

t	=	time period [h]
R(t)	=	reliability at time t
M(t)	=	reliability at time t
β	=	Weibull distribution shape parameter
η	=	Weibull distribution characteristic life [h]
μ	=	Mean in the logarithmic domain, lognormal distribution
σ	=	Standard deviation in the logarithmic domain lognormal distribution
AF	=	Availability Factor
EAF	=	Equivalent Availability Factor
MTTF	=	Mean Time to Failure
MTTR	=	Mean Time to Repair
RPN	=	Risk priority number
S	=	Severity
O	=	Occurrence
D	=	Detection
MC	=	Maintenance Cost
RI	=	Risk Index
Cf	=	Fixed cost of failure (cost of spare parts)
DT	=	Down Time
Cv	=	Variable cost per hour of down time
PLC	=	Production Loss Cost
PL	=	Production loss in Mega Watt hour
SP	=	Selling price of generated electricity
FDT	=	Failure Defense Task
MPI	=	Maintenance Prioritization Index
POH	=	Sum of all hours experienced during Planned Outage (PO) + Planed outage Extension (PE) of any Planned Outage (PO)
MOH	=	Sum of all hours experienced during Maintenance Outage (MO) + Maintenance Outage Extension of any Maintenance Outage (MO)
SH	=	Service hours, Sum of all Unit Service Hours
PH	=	Periods hours, Number of hours in the period being reported that the unit was in the active state.
AH	=	Availability hours, Sum of all Service Hours (SH) + Reserve Shutdown Hours (RSH) + Pumping Hours + Synchronous Condensing Hours.
EFDH	=	Each individual Forced Derating (D1, D2, D3) is transformed into equivalent full outage hour(s). This is calculated by multiplying the actual duration of the derating (hours) by the size of the reduction (MW) and dividing by the Net Maximum Capacity (NMC), these equivalent hour(s)are then summed
ESDH	=	Equivalent Scheduled Derated Hours, Each individual Planned derating (PD,DP) and Maintenance Derating (D4, DM) is transformed into equivalent full outage hour(s). This calculated by multiplying the actual duration of the derating (hours) by the size of reduction (MW) and dividing by the Net Maximum Capacity (NMC). These equivalent hour(s) are then summed.

This paper presents a new methodological maintenance development to yield an integrated maintenance program. In this method, a new approach to identify the most critical components in a thermal power plant by combining the concepts of RCM, RBM and CBM. The criticality is associated with the component reliability and the risk of its failure. The higher the criticality of the component, the more technical and financial resources should be expended in the maintenance activities to keep the thermal power plant availability for operation. The method results a FDT aiming at the overall thermal power plants availability. FDT is defined as maintenance activities including preventive maintenance and condition monitoring tasks.

This paper is structured in the following way: Section 1 provides a background of the methodological maintenance development. The steps of the methodological maintenance development are explained in Section 2. Selected example of application to thermal power plant is discussed in Section 3. Conclusions are then discussed in the last section.

2. Development Method

The first step is the elaboration of a thermal power plant functional tree that describes the functional relationship between the subsystems of equipment to the relationship between – components. The structure of the system is described in the function tree from top to bottom. The top level describes the main function of system analysed. The bottom level describes the components of the system. Between of them there are several equipment. All the components forming the function of the level above and subsequently formed the main functions of the system. Event of components will affect the above system-level events and subsequent events on top system. This functional tree will be the basis for further process analysis on the method developed.

The next stage is to perform FMEA analysis for each component mentioned in the function tree. Each component analysed is based on modes of damage and the effects of the system. FMEA can be seen from the analysis of the most critical components. This analysis is to identify the level of criticality of each component and then determined the sequence of critical levels of all components. The critical level is determined severity, occurrence, and detection. The order of criticality based FMEA analysis denoted with ranking priority number (RPN) which is multiplication of severity (S), occurrence (O) and detection (D).

The level of criticality of each index is denoted by numerical code of the value of 1 to 10. A value of 1 indicates the lowest critical level and the value of 10 indicates the highest level of criticality. Range 1 to 10 illustrates the qualitative scale defined through expert panel and [22] on this study. Expert panel consists of experienced technicians, engineers and planners in maintenance activities the thermal power plant.

Based on the severity, component failure causing unavailability of the system is categorized as critical components. This unavailability caused by the activities of the component repair failed. The longer time to repair means that the higher the level of criticality of the component. The severity values that categorized critical components begin grades 6. The description of the severity of the value of 6 to 10 is given in Table 1.

The occurrence includes criteria for determining the criticality of components. Components with the emergence of failure in a short time mean lower component reliability.

Table 1
Critical severity index of the thermal power plant

Critical Index	Description
(6) Major	The potential component failure causes the failure of equipment , but does not cause damage to other components but the equipment is still available, the failure resulted trip equipment, potential damage to the environment, failure potentially not meet government regulations regarding environmental, failure lead to or replacement of components which fail, failure resulting plan trips , and can be recovered in less than 2 days, ability ramp rate down to 45 %, impact decrease in efficiency increase 15 %, failure of the parent system functions in one (8 hours) or 100 % redundancy
(7) Severe	Potential failure hardware components cause but no damage other components, potential severe damage to the environment, failure to comply with the government resulted in no, the failure resulted in the repair or replacement of components failed ,plant / equipment not be operated hearts Short Time (2-7 days),ability street level down- up to 55 %, impact efficiency 18 % reduction failure parent system function hearts 4 hours redundancy or 50 %
(8) Very Severe	The potential component failure causes the failure of equipment , but does no cause damage to other components, the failure resulted trip equipment, inflicting severe damage to the environment, failure result does not meet government regulations, the failure resulted in the repair or replacement of components which fail, plant / equipment cannot be operated in a long time (7 days -1 month), ability ramp rate down to 65 %, impact decrease in efficiency of 21%, failure of the parent system functions in 1 hour or redundancy of 50 %
(9) Hazardous	Failure cause severe damage to the components or other equipment, equipment failures result trip, cause harm to the environment , hazardous material leaks into the environment, failure result does not meet government regulations, the failure resulted in the repair or replacement of many components, plant / equipment cannot be operated in a long time (1-3 months), ability ramp rate down to 75 %, impact reduction efficiency of 25 %,system malfunction within 30 minutes or no back up
(10) Catastrophic	Failure cause severe damage to other equipment, the failure resulted trip a system equipment, cause harm to the environment , hazardous material leaks into the environment, failure result does not meet government regulations, the failure resulted in the replacement of almost all components, plant / equipment cannot be operated in a long time (> 3 months), ability ramp rate of up to > 75 %, system failures have a major impact on reducing the efficiency , failure of the parent function immediately or no back-up

Unavailability is often caused by low reliability of components and should be avoided. The higher rate of occurrence means that the lower the reliability of components and it also means that the higher the degree of criticality. Criticality components based occurrence index determined by the maintenance cycle. In the case of this study, the major inspection & overhaul (MI) is done every four years. Component failure that occurred prior to the MI is categorized critical component. This means that failure has occurred prior to the preventive maintenance. Category critical component starts from the value 6 in which the failure can occur before four years or the preventive maintenance performed. The description occurrence index of the value of 6 to 10 is given in Table 2.

Table 2
Critical occurrence index of the thermal power plant

Critical index	Description
6	Failure occurred under 4 years
7	Failure occurred under 2 years
8	Failure occurred under 1 years
9	Failure occurred under 6 months
10	Failure occurred under 3 months

In general, the criticality of components defined the possibility of failure occurring during the system operation. For mechanical-electrical system component damage is not sudden. Failure was preceded by a decrease in reliability and this can be monitored. Components that failure cannot be monitored with existing technology categorized critical components. Level of the monitoring capabilities the failure of component denoted by detection index. Components are most easily detectable failure given index value 1. Index value 10 for components failure cannot be detected with existing technology. In the case of thermal power plant, the component failures can be detected. This means there is no critical component categories based on detection. All the components can be controlled to avoid a failure during the system operation.

FMEA analysis produces a sequence component criticality. Then the next step is to develop a failure diagnostic procedure that allows rapid recovery actions in case of failure occurrence. That procedure determines the root cause of the component failure aiming at directing technicians to investigate the cause of the detected failure.

We use Fault Tree Analysis (FTA) technique for diagnosing a failure. This technique is suitable for tracing the cause of failure to a complex system with many components [23]. Search the cause of the failure is done by decomposing the groove cause the failure from system to the subsystems to component level. Thus, using FTA in the developed method can improve maintainability by speed-up failure diagnosis.

FTA generates a series of maintenance actions that include preventive maintenance task and condition & assessment task. A set of maintenance actions aimed at avoiding the unexpected failures and is called Failure Defence Task (FDT) in this study. This FDT also FDT term commonly is used in the practice of maintenance of the case study. FDT can be either repair or replacement actions. The repair action restores the component like a new condition as replacement actions.

Determination of the critical level components in the FMEA analysis has not considered the aspect of risk associated with the costs of the failure. Risk will need to be considered because the cost is an important factor in managing a thermal power plant. Risk of component damage caused substantial costs should be prioritized in maintenance. This study considers the risk in determining the criticality of components through risk analysis.

There are two steps in the analysis of risk i.e. the risk assessment and evaluation. At this step of the risk assessment were calculated probability of occurrence of failure and its consequences. That probability is obtained through the use of software Weibull++ (Reliasoft, 2003). The consequence is calculated from the cost of repair required and the cost of lost production.

The calculation of the cost of repair using Eq. (1) in [14],

$$MC = C_f + DT.C_v \quad (1)$$

And the calculation of the cost of lost production using Eq. (2) in [14],

$$PLC = DT.PL.SP \quad (2)$$

The second step is to calculate the risk evaluation. This evaluation result the risk index which is obtained from dividing the value of risk assessment to the level of acceptable risk in [23]. The component criticality is determined by the value of the risk index. In this study, the critical component is a component that has a risk index above 0.8. Conversely, components that have a risk index of less than 0.8 are not considered critical components. Thus the critical level is not only determined by the reliability aspects but involves aspects of risk.

Two important aspects of maintenance have been considered to determine the criticality of components, namely reliability and risk. The next step is to set maintenance priority based on those aspects. Weighted RPN is extended the definition of RPN by multiplying it with a weight parameter, which characterize the importance of the failure causes within the system [24]. In the same manner, we use to calculated Maintenance Priority Index (MPI) which to determine the maintenance priority of components. The higher value of MPI means higher priority component in the maintenance.

The maintenance priority is indicated by the value of MPI that obtained by using Eq. (3).

$$MPI = RPN \quad x \quad RI \quad (3)$$

MPI value becomes an important element in preparing the maintenance program. Component with the highest MPI value is a top priority in the maintenance. The MPI value also used to determine condition monitoring & assessment plan. Condition monitoring is most required for groups of components that have a high value of MPI. Maintenance action based on condition monitoring is necessary to maintain the component with a high level of criticality is not fail during the system operation. Such components failure reduces the availability significantly and produces great risk costs.

The combination of MPI, FDT and condition monitoring shows three important aspects of the maintenance has been integrated in setting up a maintenance program that is called the integrated maintenance program. This program includes the type of periodic preventive maintenance actions, determination the type of condition monitoring (on-line or off–line) and maintenance intervals. Determining the type of maintenance actions are based on the FDT of each component that has been formulated at the FTA analysis.

The integrated maintenance program is formed to improve the availability of power plant. Three aspects are important in the maintenance of the reliability, risks and conditions have been adopted in this maintenance program. Each of these aspects has been used in the RCM, RBM and CBM. The development of this program has been to integrate two maintenance bases, namely time and condition-based maintenance.

The final step of the methodology is the analysis of reliability and availability. This analysis is done to see the effect of the implementation of an integrated maintenance program to improve the availability of the system. The reliability analysis is based on the time to failure data analysis. Meanwhile, the availability analysis is based on the analysis of the repair time. The effectiveness of the maintenance methodology can be measured from the extent to which the increased availability after application of the integrated maintenance program.

The main steps of the methodology of maintenance proposed are shown as Fig. 1.

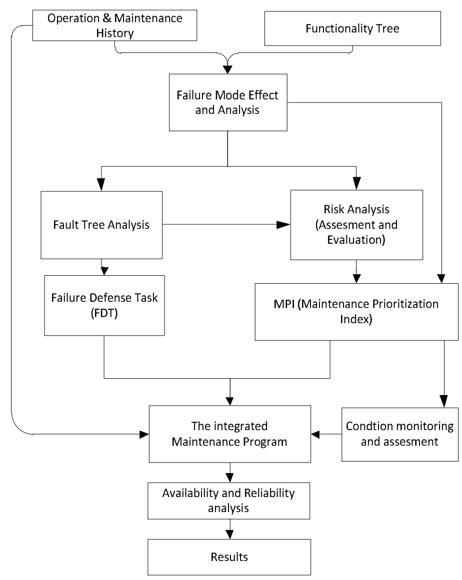

Fig.1. The main steps of the methodological of maintenance developed

In the methodology, the integrated maintenance program is formed of four input factors, namely the data history of operation and maintenance, FDT, MPI and condition monitoring. The mechanism of the formation of the integrated maintenance program from four input factors is given as Fig. 2.

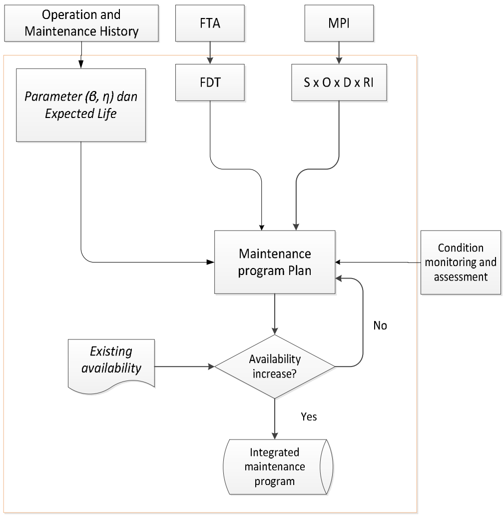

Fig. 2. Flow chart of the integrated maintenance program

3. Application

The method has been developed is applied to the thermal power plant Unit 4 with an output capacity of 200 MW, located in North-Jakarta. They have 1664 kinds of mechanical and electrical components. The reliability and availability of the thermal power plant are simulated based on a three-year failure database.

3.1. Functional tree

The functional tree the power plant is presented in Fig. 3 and was divided into thirteen subsystems. For detail of the functional tree of the system which is divided into subsystems until each component, each one performing a specific function in connection with the subsystem main functions. A failure in a component at the bottom of the tree affects all subsystems above it, causing a possible degradation in the thermal power plant operation, represented by any reduction in the nominal power output or even environmental degradation. The tree was according developed according to the operation manual furnished by the manufacturer.

3.2. Failure mode and effect analysis

The FMEA analysis was performed for each component listed in the end of a given branch of the functional tree. The failure modes for the components were developed according to manufacturer’s information’s and other failure analysis from FMEA team. The FMEA team identifies, evaluates, and prioritizes potential failures [25].

The analysis pointed out that the most critical components for the thermal power plant are:

1. Cooling water system: Shaft of main circulating water pump.
2. Feed water system: thrust bearing of BFP variable speed hydraulic coupling, journal bearing of scoop tube assy, Mechanical seal of BFP#A, shaft of scoop tube assy, primary shaft of variable speed hydraulic coupling.
3. Boiler system: Platen super heater inlet header, Finishing superheater inlet header, Primary superheater tube, Primary superheater inlet header, Finishing superheater element, Primary reheater element, Finishing reheater element, Primary reheater inlet header, Boiler pressurized second superheater.
4. Turbine system: Thrust pad passive side, Thrust pad active side, Turbine journal bearing, Journal bearing tilting pad, Low Pressure rotor blade, Main stop valve stem, High pressure rotor blades.
5. Generator system: Rotor copper conductor, Winding copper, Stator winding insulation.

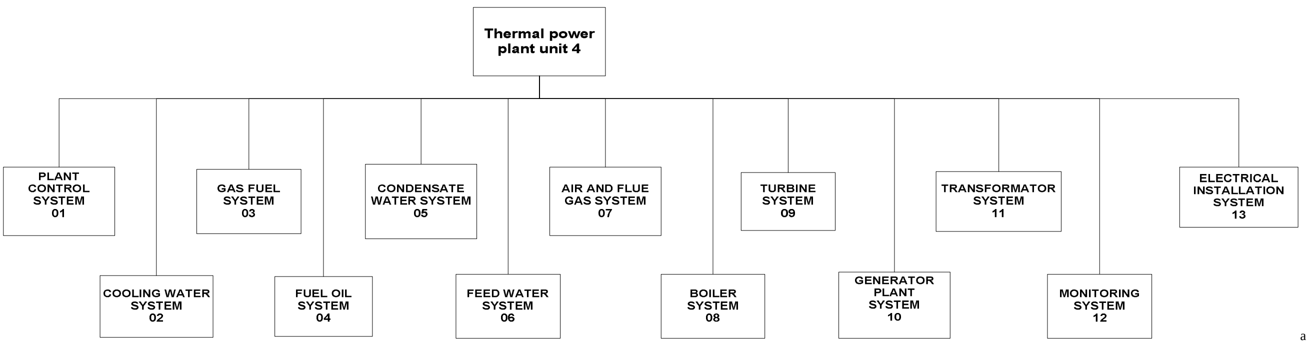

Fig. 3. The functional tree of Thermal power plant Unit 4

3.3. Fault tree analysis

The functional tree is fundamental for the understanding of the functional relation between system components. At the subsystem system level, the fault tree of thermal power plant is showed in Fig. 4. This fault tree can be elaborated including lower subsystem until their components at the bottom level. The events at component level are named a basic event. These events are analyzed to plan a maintenance program. Based on the functional tree, we use the fault-tree technique to identify the component failure of combination of component failures that cause the failure of system or subsystem. For those components a maintenance program can be formulated to avoid their failures. The maintenance program consists of preventive maintenance and condition-monitoring tasks. In the present study, those tasks is named failure defense task (FDT).

3.4. Failure defense task

The maintenance program of thermal power plant is based on four or five year cycles depending on system condition. Some annually based basic preventive tasks are performed. In the middle of the cycle a more complex inspection is performed. After that the basic tasks are performed annually and at the end cycle major inspection and overhaul maintenance is performed.

Based on the results of the FMEA and Risk analysis, the RCM and RBM concepts can be used to recommend FDT to those components that have a criticality index greater than 6 (severity) and/or 6 (occurrence) and/or 0.8 (risk index). The failure of those components can cause the unavailability of the thermal power plant. In the present study the detectable index do not used as critical index because all the component failures can be detected by technology available.

Generally, the power plant has a complex monitoring system based on temperature, pressure, vibration, chemical concentrates, acoustic, gas, current measurements and analysers. That system is used to monitor and assess the real-time condition of the critical components of the thermal power plant allowing the use of FDT to improve the system availability. Those data can be used to define the trend and pattern in the equipment condition and a limit value must be selected as a potential failure indicator.

That value allows identification of the alert level, providing to schedule FDT before failure occurs. The analysis is used for the implementation of the FDT. Moreover, most of the critical components of the thermal power plant can be assisted with FDT.

3.5. Risk analysis

Risk analysis is done to identify the level of risk arising from a component failure to the system. There are two consequences of the costs incurred as a result of failure of the components i.e. the maintenance cost and production loss cost. Those costs are calculated respectively using Eq. (1) and (2). In the case of thermal power plant Unit 4, PLC calculation per hour is around US$ 11,840. Results calculated from both equations for each component are added.

Then, the total of those costs is divided by the value of acceptable risk to obtain risk index. The acceptable risk was determined based on yearly maintenance expenditure Unit 4 (US$ 2,080,000).

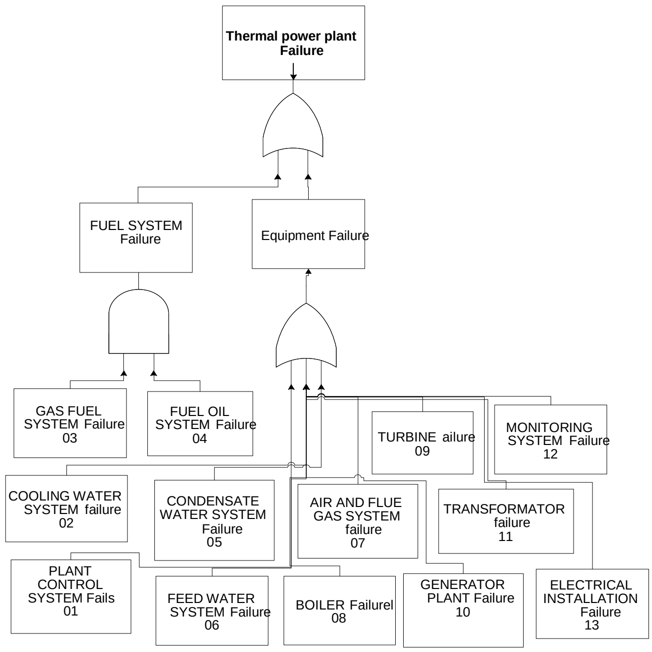

Fig. 4. The fault tree of the thermal power plant

3.6. Maintenance Priority Index

MPI value calculation applied to all components of the bottom of the tree function. This value is obtained from the calculation by using Eq. (3). Once identified based on the criticality index, from 1664 components in the system there are 858 types of critical components. This criticality is based on one of the index value of the index the severity, occurrence and risk. In this paper all critical components are not shown. The highest value is on the blade of the turbine system components. This component is certainly not suffered failure during system operation. Therefore, the components which have high MPI values should get priority maintenance. Maintenance priorities presented within the scope of activities of the FDT.

3.7. Reliability and Availability Analysis

Reliability can be defined as the probability that a system the probability that a system will perform properly for a specified period of time under a given set of operating conditions. For the thermal power plant the failure is any component failure that causes incapacity of generating the nominal power output.

The reliability analysis is performed on the power plant. It is based on the time to failure data analysis. Probably the single most used parameter to characterize reliability is the MTTF. It is just the expected or mean value of the failure time, expressed as in Eq. (4):

$$MTTF = \int_0^\infty R(t)dt \qquad (4)$$

Random failures constitute the most widely used model for describing reliability phenomena. They are defined by the assumption that the rate of failure of a system is independent of its age and other characteristics of its operating history. The Weibull probability distribution is one of the most widely used distributions in reliability calculations involving time related failures. Through the appropriate choice of parameters a variety of failure rate behaviours can be modelled, including constant failure rate, in addition to failure rates modelling both wear-in and wear-out phenomena.

The thermal power plant is modelled as one block. For that block the reliability and maintainability distribution are estimated based on failure data recorded. The two-parameter Weibull distribution, typically used to model wear-out that failure rate increases. This distribution represented in Eq. (5):

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (5)$$

The distribution parameters are estimated through the use of parametric estimation methods that fit the distribution to the 'time to failure' data. There are procedures for estimating the Weibull distribution parameters from data, using what is known as the maximum likelihood estimation method. For the thermal power plant reliability analysis the software Weibull ++ version 6 (Reliasoft,2003) was used for parameter estimation.

The results of parameter values estimation for the thermal power plant are $\beta = 5{,}3533$ and $\eta = 15211$. The thermal power plant presented 39 failures that caused equipment unavailability in the analysis period. Several of those 22 failures occurred in the first two operational years. Most of them were related to leakage in line drain gland turbine and economizer. In the last three years there were 1 leakage in line drain gland and 2 leakages in glad seal steam. The failure root-cause was improperly monitoring feed water, pressure and temperature.

The failures that may affect thermal power plant availability were associated with components listed at the bottom of functional tree branches presented in Fig. 2 and were considered as critical components in the FMEA analysis.

The other aspect from reliability related to increasing availability is maintainability that is defined the probability of an equipment will be repaired in a given period of time. Typically, the describing of the probability distribution was used lognormal distribution to model the time to repair distribution of complex systems. The maintainability can be expressed according to Eq. (6) in [21]:

$$M(t) = \Phi\left(\frac{\ln t - \mu}{\sigma}\right) \quad (6)$$

Based on the time to repair database for the thermal power plant using the software Weibull ++ Version 6 (Reliasoft, 2003). The lognormal distribution parameters for maintainability modelling are $\mu = 7.9652$ and $\sigma = 0.9333$.

The thermal power plant is an electrical-mechanical complex system. It means there are two categories of the component, i.e. electrical and mechanical component. In mechanical component, the causes of failure are likely to be quite obvious. The primary time entailed in the repair is then determined by how much time is required to extract the damage parts and install the new component. In contrast, If an electronic device fails, maintenance personnel may spend most of the repair procedure time in diagnosing the problem, for it may take considerable effort to understand the nature of the failure well enough to locate the part that is the cause. Conversely, it may be a rather straightforward procedure to replace the faulty component once it has been located.

Once the reliability and maintainability parameters are calculated the system availability can be estimated. The availability is controlled by two parameters. Firstly, MTTF which is a measure of how long, on average, the thermal power plant will perform as specified before an unplanned failure will occur, being associated with equipment reliability. Secondly, MTTR which is a measure of how long, on average, it will take to bring the equipment back to normal serviceability when it does fail. Although reliability can be at least estimated during the thermal power plant design stages, its availability is strongly influenced by the uncertainties in the repair time. Those uncertainties are influenced by many factors such as the ability to diagnose the cause of failure or the availability of equipment and skilled personnel to carry out the repair procedures. In the case of a thermal power plant, the same equipment model can present different availability in different sites due to difference in the skill of personnel responsible for maintenance.

Considering the thermal power plant operating one year or 8760 hours and using parameters of the reliability and maintainability probability distribution is found the availability for the thermal power plant given in Table 4. Availability is an index dependent on reliability and maintainability. The availability will increase if the reliability increases and/or the maintainability increase.

In Table 4, the average availability of thermal power plant within 2008 to 2012 is 76.95 %. The thermal power plant analysed in the present study has lower availability than the value presented in the NERC. The availability can be increased through FDT, These maintenance tasks will reduce the probability of failure during the thermal power plant operating.

3.8. Availability Improvement

The maintenance policy performed in the present study is called FDT that consists of the preventive and predictive maintenance tasks. FDT is the results of the availability analysis listed in Table 4. Management can implemented our recommendation of maintenance improvement to increasing the thermal power plant availability.

Implementation of the FDT improves two aspects of the maintenance performance i.e. reliability and maintainability. The chance of those performances can be seen in Fig. 6 and 7.

Fig. 6 shows the graphic of the thermal power plant reliability in two periods i.e. 2011 to 2012 and 2013 to 2014. The first period describes the condition which maintenance tasks are not improved yet. The second cycle describes the condition which maintenance tasks have implemented the FDT. The comparison of those provided the reliability improvement after FDT performed. The Weibull distribution parameter values after the improvement are $\beta = 7.3307$ and $\eta = 17721$. Fig. 7 shows the graphic of the one's maintainability in the same period. In this graphic, the maintainability after FDT performed higher than that before FDT performed. Those graphics show FDT has increased the reliability and maintainability of the thermal power plant and hence the availability of the thermal power plant increases which is shown in Table 5. The lognormal distribution parameter values for maintainability after improvement are $\mu = 5.6239$ and $\sigma = 2.1182$.

Table 4
The availability before FDT performed

Year	SH	POH	MOH	FOH	RSH	AH	PH	EFDH	ESDH	EAF
	(HOUR)									
2008	7056.53	0	1261.62	37.15	428.70	7485.23	8784	397.88	635.04	73.46%
2009	6403.42	1413.80	459.88	455.73	27.17	6430.59	8760	152.99	421.58	66.85%
2010	501.47	1066.00	1155.62	198.62	638.30	6339.77	8760	135.28	184.73	68.72%
2011	1105.03	1416.00	45.50	0	6193.47	7298.50	8760	4.11	0	83.27%
2012	6649.84	0	325.15	335.38	1473.62	8123.46	8784	2.49	0	92.45%
Average										76.95%

Fig.6. The reliability comparison between before and after FDT

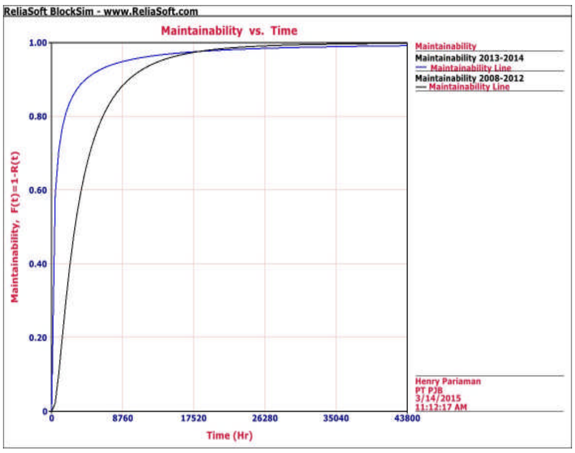

Fig. 7. The availability comparison between before and after

Table 5 shows that the average level of availability achieved 94.59 %. This value is higher than the average level of availability is achieved before applied FDT. This increasing can be seen clearly from the FOH which shows the frequency of occurrence of unexpected failure. The condition prior to the FDT, the total time of repair due to damage to the components is 705.53 hours and this value decreased after FDT be 33.82 hours. This means FDT applied can reduce unplanned maintenance activities and further increase the availability of the system.

4. Conclusion

In this paper we proposed a new methodological maintenance development for a complex system with high production loss such as thermal power plant with high capacity output. Such a system, availability will become the most important factor that will be concerned by top management. The method developed is used to increase the system overall availability. This method has considered maintenance based of reliability, risk and condition in which these three maintenance basis have not been considered in an integrated manner. The integration of these three maintenance basis is expected to increase the availability of better than previous methods.

The proposed method has a new rule of the determining critical components based on FMEA, FTA and risk analysis. Analysis performed yields MPI for action and maintenance planning, is called FDT. MPI also is used to prepare the procedure of condition monitoring for critical components. Integration between FDT and condition monitoring yields an integrated maintenance program that increases the availability of system.

The method developed has been applied to the case of a thermal power plant with an output capacity of 200MW. Availability analysis is done to determine the effectiveness of an integrated maintenance program. Application of this method follows the maintenance cycle that has been run on the system in the present. From the comparison of performance between before and after implementation of the proposed maintenance program found that the average availability of the system within a period of two years increased from 76.95% to 94.59%. Thus, this method can improve the system performance especially the availability of the system.

Table 5
The availability after FDT performed

Year	SH	POH	MOH	FOH	RSH	AH	PH	EFDH	ESDH	EAF
	(HOUR)									
2013	7323.94	912	24.00	0	500.07	7824.00	8760	0	0	89.32%
2014	6320.52	0	0	9.82	2429.67	8750.18	8760	1.72	0	99.87%
Average										94.59%

Source: The operation and maintenance data of the thermal power plant

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