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AVAILABILITY ANALYSIS OF THE INTEGRATED MAINTENANCE TECHNIQUE BASED ON RELIABILITY, RISK, AND CONDITION IN POWER PLANTS

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ABSTRACT

The availability of power plants is of utmost importance in a power system. The availlability of a power plant is determined by its reliability and maintainability, which results from the plant's maintenance program. Commonly used maintenance techniques for power plants include reliability-centered maintenance (RCM), risk-based maintenance (RBM), and condition-based maintenance (CBM) as well as their combination. This study aims to analyze the respective system availability that results from each of the three maintenance techniques and examines the system availability of the integrated maintenance technique, which is based on reliability, risk, and condition. The availability analysis is performed by developing a mathematical model based on the maintenance programs produced by each maintenance technique. The availabilities of the RCM, RBM, CBM, and integrated maintenance techniques are 81.56%, 81.02%, 84.92%, and 90.07%, respectively.

Keywords: Availability analysis; Integrated maintenance technique; Power plant; Simulation

1. INTRODUCTION

Power plants must have high availability to meet electrical needs. Availability is the probability that a system can be used or operated as needed (Dhillon, 1999). Availability can be increased by enhancing the reliability and/or maintainability of the system (Carazas & Souza, 2010). Reliability can be improved during the product design and/or product development phases while maintainability can be increased during the development of maintenance techniques.

In general, maintenance programs seek to increase a system's reliability and availability. For power plants, researchers have developed maintenance programs and techniques with the goal of maximizing availability. Each maintenance technique results in different maintenance packages and determines the obtainable level of availability. Several maintenance techniques have been developed (Garg & Deshmukh, 2006): preventive maintenance (PM), condition-based maintenance (CBM), total productive maintenance (TPM), computerized maintenance management system (CMMS), reliability-centered maintenance (RCM), predictive maintenance (PDM), maintenance outsourcing, engineering concept maintenance (ECM), sensor

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maintenance management (SMM), and risk-based maintenance (RBM). The maintenance techniques commonly used in power plants are RCM (Moubray, 1997; Rausand, 1998; Eisinger & Rakowsky, 2001; Eti et al., 2007; Carazas & Souza, 2009; Volkanovski et al., 2009; Li & Gao, 2010; Bhangu et al., 2011; Carazas et al., 2011; Fischer et al., 2012), RBM (Carazas & Souza, 2010; Carazas et al., 2011; Aven, 2003; Yatomi et al., 2004; Krishnasamy et al., 2005; Nordgard et al., 2005), and CBM (Stephan & Laird, 2003; Li & Nilkitsaranont, 2009; Emmanoulidis et al., 2010). To improve maintainability, combinations of maintenance techniques, such as RCM and RBM (Selvik & Aven, 2011) or RCM and CBM (Niu et al., 2010), have also been considered.

Despite their significant availability gains for power plants, maintenance techniques may benefit from further improvement to maximize power plant availability. According to Garg and Deshmukh (2006), integrated maintenance techniques can be used to improve maintenance performance. The use of integrated maintenance techniques is expected to yield higher availability compared to the use of an individual maintenance technique. Pariaman et al. (2015a) demonstrated that the implementation of integrated maintenance techniques will result in higher availability in thermal power plants. Determining the availability of a unit requires a mathematical model. Jiang (2010) utilized a linear combination of the cumulative distribution function CDF) and the cumulative hazard function (CHF) to determine the expected failure of components, which is an important parameter in calculating availability.

Although it is expected that the integration of three maintenance techniques results in better availability than the use of a single technique, there is currently no study that integrates the RCM, RBM, and CBM maintenance techniques and examines how that combinational approach affects availability. This study introduces a mathematical model for determining the availability improvements achieved through conventional maintenance techniques—namely, RCM, RBM, and CBM—as well as integrated maintenance techniques involving RCM, RBM, and CBM. Furthermore, this paper compares the effectiveness of these maintenance techniques in improving a system's availability.

2. METHODOLOGY

2.1. Weibull Distribution Function

Three types of behavioral failure can be modelled by the Weibull distribution function: decreasing failure rate (DFR), constant failure rate (CFR), and increasing failure rate (IFR). Engineers performing reliability analysis often assume that time-dependent failure rates follow the bathtub failure rate curve (Dhillon, 1999), as shown in Figure 1.

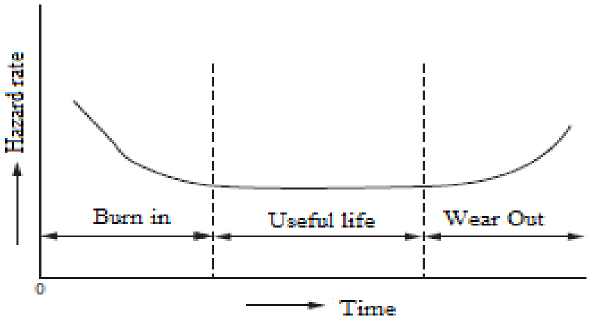

Figure 1 Bathtub curve

Figure 1 shows three distinct periods: the burn-in period, useful life period, and wear-out period. The failure rate decreases during the burn-in period (DFR), and failures in this period can be caused by several factors such as poor quality control, inadequate materials, incorrect product usage, inappropriate test specifications, unsuitable installation, inappropriate manufacturing, unfinished final tests, bad packaging, inappropriate representative training, and power surges. During the useful life period, the failure rate is constant (CFR), and failures are random and unpredictable; these failures may be caused by noncompliance regarding design margins, unsuitable environments, undetectable defects, and human error. The wear-out period begins after the useful life period. During the wear-out period, the failure rate increases (IFR), and these failures are caused by accumulation of age-related damage, misalignment, corrosion, fatigue, and creep.

2.2. Maintenance Function Structure

As shown in Figure 2, the inputs of a maintenance technique are the maintenance interval, T_{ip}, and the duration of repair and maintenance actions, T_r and T_p, respectively. Furthermore, T_{ip}, T_r, and T_p become decision variables for maximizing the availability, which is the output; the selected maintenance technique determines the values of these decision variables. Disturbances occur in the forms of deterioration and process variation, which can be found in the maintained unit and become uncontrolled factors. This functional structure becomes the basis of analysis for describing the performances of RCM, RBM, and CBM. The availability, $A(T_{ip}, T_r, T_p)$, must be expressed mathematically for analysis using maintenance simulation techniques.

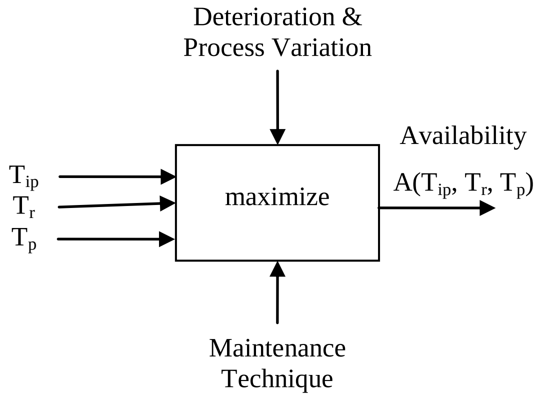

Figure 2 Functional structure of maintenance activities

Huge entities, such as power plants, involve complex systems. A system with a single component unit, which can represent the multi-component unit, is modelled before studying the complex system. Figure 3 shows a diagram of a single component unit with repairable damage (i.e., a repairable system).

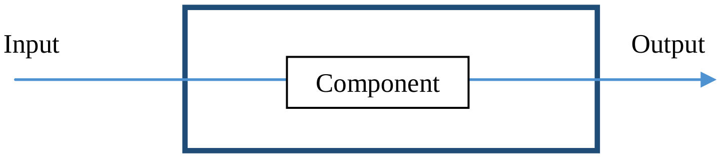

Figure 3 Single component system

Every unit is repaired to recover its condition. After failure, the system is repaired in a time duration of T_r, after which the status of the system is as good as new. Before/between failures, PM, such as overhaul, may be performed at maintenance intervals of T_{ip}, lasting for a period of T_p. The repair duration will always exceed the maintenance duration, i.e., $T_r > T_p$, because maintenance is a planned action with well-prepared resources such as laborer's, equipment, materials, and tools. Figure 4 shows the reliability history of a system that suffers two failures before its first maintenance interval.

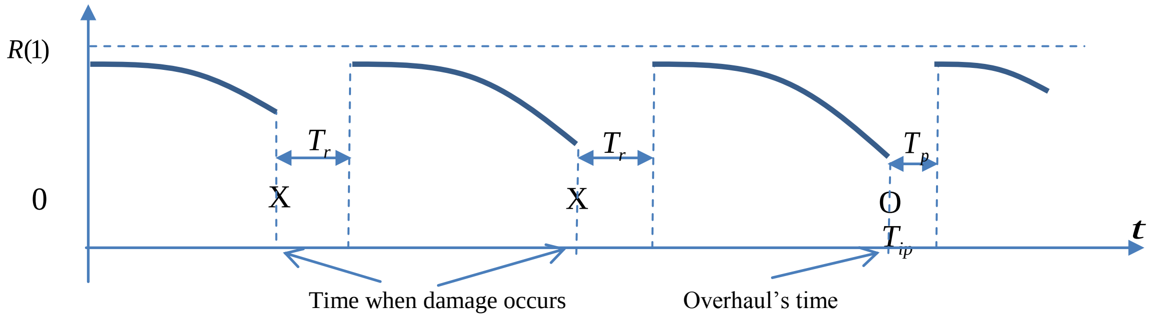

Figure 4 Characteristic of reliability during one interval maintenance

2.3. Mathematical Model of Availability

Because failures during maintenance intervals occur randomly, failures follow a stochastic process. For any failure repaired during a duration of T_r, the expected number of failures, $m(t)$, during the maintenance interval, T_{ip}, is obtained by using the renewal equation. In the case of a distribution, the amount of damage follows a Weibull distribution, so $m(t)$ can be obtained through numerical approaches. Jiang (2010) used a linear combination of a CDF and CHF to obtain an approximation for $m(t)$:

$$m(t) \cong pF(t) + (1-p)\Lambda(t) \ , \tag{1}$$

where $F(t)$ is the CDF of damage and $\Lambda(t)$ is the CHF, $\Lambda(t) = \int_0^t \lambda(t)dt$.

The linear combination coefficient, p,is obtained using Equation 2.

$$p = 1 - \exp\left(-\left(\frac{\beta - 1}{0.8731}\right)^{0.9269}\right), \tag{2}$$

where β is the shape parameter of the Weibull distribution. Based on Equation 1, the approximated equation can be written as Equation 3:

$$m(t) \cong p\left[1 - \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right)\right] + (1-p)\left(\frac{t}{\eta}\right)^{\beta} \ . \tag{3}$$

Combining Equations 2 and 3, the expected number of failures at t is

$$m(t) = \left(1 - \exp\left(-\left(\frac{\beta - 1}{0.8731}\right)^{0.9269}\right)\right)\left[1 - \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right)\right] + \exp\left(-\left(\frac{\beta - 1}{0.8731}\right)^{0.9269}\right)\left(\frac{t}{\eta}\right)^{\beta} . \tag{4}$$

The functional structure of maintenance activities (Figure 2) can be described with a mathematical model. The availability of a system is the relative uptime (i.e., the ratio of the uptime to the sum of the uptime and downtime). The uptime is the time during which the power plant unit can be operated to produce electrical power. The downtime is the time required to do maintenance (i.e., overhaul/preventive or repair). If no failure occurs during a maintenance interval, the availability, $A(T_{ip}, T_p)$, can be expressed as

$$A(T_{ip},T_p)=\frac{T_{ip}}{T_{ip}+T_p}\ . \tag{5}$$

Based on Equation 5, if T_p decreases, then $A(T_{ip},T_p)$ will increase. Reducing the duration of PM, T_p, corresponds to increased maintainability, which can be achieved by increasing the rate and accuracy in diagnosis and the readiness of spare parts.

However, if failure occurs during the maintenance interval, and repairs are performed, then the availability is affected by the repair duration, T_r, and the amount of damage acquired during the maintenance interval, $m(T_{ip})$. Figure 5 shows the influence of failures on system availability.

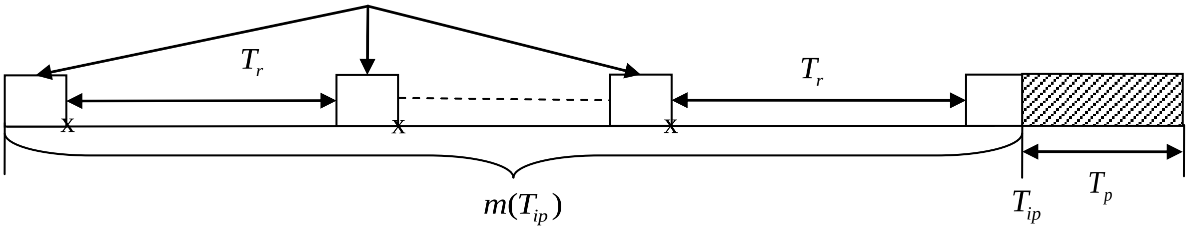

Figure 5 Influence of damage on availability

As shown in Figure 5, each instance of failure reduces the uptime. For a Weibull distributional function, $m(T_{ip})$ is determined according to the reliability parameters, β and η. Maintenance activities do not influence β and η; therefore, $m(T_{ip})$ can be written as $m(T_{ip}|\beta,\eta)$. The availability is calculated using Equation 6.

$$A(T_{ip},T_p,T_r\,|\beta,\eta)=\frac{T_{ip}-m(T_{ip}\,|\beta,\eta)T_r}{T_{ip}+T_p}\ ; \tag{6}$$

thus,

$$A(T_{ip},T_p,T_r\,|\beta,\eta)=\frac{T_{ip}-\left(\left(1-\exp\left(-\left(\frac{\beta-1}{0.8731}\right)^{0.9269}\right)\right)\left[1-\exp\left(-\left(\frac{T_{ip}}{\eta}\right)^{\beta}\right)\right]+\exp\left(-\left(\frac{\beta-1}{0.8731}\right)^{0.9269}\right)\left(\frac{T_{ip}}{\eta}\right)^{\beta}\right)T_r}{T_{ip}+T_p}\ . \tag{7}$$

Based on Equation 7, the availability is a function of T_{ip}, T_r, and T_p. The unit reliability is specified by the manufacturer. Equation 7 is used in the simulation of availability with respect to maintenance techniques.

3. AVAILABILITY SIMULATION OF INTEGRATED MAINTENANCE TECHNIQUES

In this study, simulations are performed to compare the availability of power plants that use conventional maintenance techniques according to the manufacturer's recommendations, CBM, RCM, and RBM. The study also examines maintenance techniques that integrate the three aforementioned conventional techniques. The system model developed for maintenance simulation consists of five different sub-systems that are arranged in a series (see Figure 6). The series connection means that the failure of any constituent component will cause the system to fail. The five components are defined to represent low-reliability, high-reliability, low-risk, and high-risk components. In this study, a comparison period of three years is set. The reliability characteristics of all components are assumed to follow the Weibull distribution; Table 1 lists the β and η parameters for each component.

The availability can be obtained by assuming that components do not fail simultaneously. All components have the same effective maintenance duration, T_p, of 240 hours (10 days), because even if one component is shorter, maintenance is performed concurrently. The maintenance duration, T_p, of two components, three components, four components, and five components are 360 hours (15 days), 480 hours (20 days), 600 hours (25 days), and 720 hours (30 days), respectively. The repair duration, T_r, for each component is the same: 360 hours (15 days).

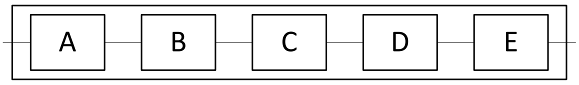

Figure 6 The structure of the system

Table 1 The parameter values of components

Component	β	η
A	2.8	9
B	2.5	13
C	1.7	15
D	2.2	20
E	2.1	23

3.1. Conventional Maintenance Technique

The conventional maintenance techniques were performed according to the manufacturers' recommendations. Maintenance is performed after the reliability component reaches 0.2. Based on the parameter values in Table 1, the maintenance schedule for each component during a 36-month period is shown in Figure 7. Meanwhile, the availability level, $A(T_{ip},T_p)$, can be obtained by calculating the expected number of failures, $m(T_{ip})$, for each component during a 36-month period (26,298 hours). The expected duration of repair can be obtained from the sum of the multiplication of the expected number of failures in each component and the repair duration. The duration of maintenance can be obtained by summing the maintenance duration of each component or combination of components at each scheduled maintenance in the maintenance program. This calculation method is used to obtain the expected duration of the repair as well as the maintenance duration. The expected duration of repair based on Table 2 is 3,449.52 hours (143.73 days), and the duration of maintenance based on Figure 7 is 1,560 hours. This value is obtained from the maintenance duration of each component: Component A (240 hours), component B (240 hours), component AC (360 hours), component D (240 hours), and component ABE (480 hours). So, the total maintenance duration of a conventional maintenance program is 1,560 hours. Thus, the availability is 80.99%.

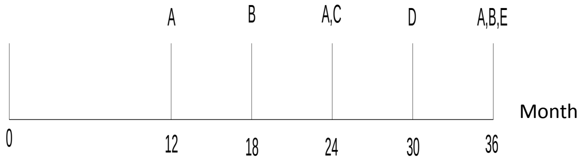

Figure 7 Conventional maintenance program

Table 2 Expected number of failures under conventional maintenance

Component	Expected number of failures
A	2.984
B	2.127
C	1.902
D	1.280
E	1.289

3.2. CBM Technique

In CBM, the reliabilities of all components are monitored. CBM ensures that there are no unprepared breakdowns; thus, all maintenance is PM. Therefore, the repair duration is equivalent to the PM duration, which is 240 hours (10 days). The expected duration of repair based on Table 3 is 397.416 hours. Thus, the availability is 84.92%.

Table 3 Expected number of failures under CBM

Component	Expected number of failures
A	7.722
B	3.256
C	2.512
D	1.671
E	1.398

3.3. RCM Technique

In RCM, the component that has the lowest reliability becomes the maintenance priority. Of the considered systems, component A has the lowest reliability based on the mean time to failure (MTTF) shown in Table 4. These values were calculated based on the parameters in Table 1.

Component A is scheduled for maintenance every 6 months (~180 days) to reduce the likelihood of failure. Every other component is scheduled for maintenance at relevant intervals that synchronize with scheduled maintenance for component A. Figure 8 shows the maintenance schedule of each component in the maintenance program according to RCM. The expected duration of repair based on Table 5 is 221.914 hours, and the duration of maintenance based on Figure 8 is 2,640 hours. Thus, the availability level is 81.56%.

Table 4 Expected MTTF for component

Component	**MTTF value (days)**
A	244
B	352
C	408
D	540
E	621

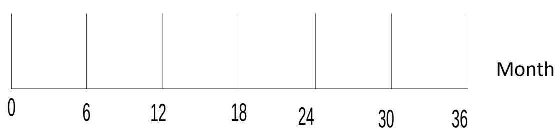

Figure 8 RCM maintenance program

Table 5 Expected number of failures under RCM

Component	Expected number of failures
A	1.302
B	1.494
C	1.533
D	1.018
E	0.818

3.4. Maintenance Technique of RBM

In RBM, the highest risk component becomes the maintenance priority. Khishanasamy et al. (2005) explained that high risk has an index value above 0.8, medium risk has a range between 0.4 and 0.8, and low risk has an index below 0.4. Components that have a risk index of 0.8 or more are classified as critical components. In this paper, it is assumed that component C is the only component in the system under study that has a high-risk index, as component C's index is 0.892.

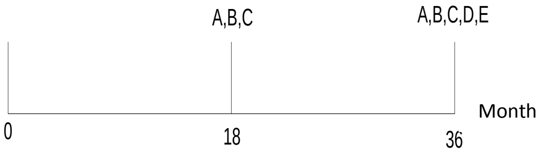

Figure 9 RBM maintenance program

The maintenance interval of component C is reduced from the 24-month interval recommended by the manufacturer to 18 months to reduce the failure risk of component C. This change of maintenance interval reduces the risk index. The risk index of component C is below 0.8. The other components are assumed to have a low-risk index. The maintenance schedules for the other components are adjusted to coincide with the maintenance schedule of component C. Figure 9 shows the maintenance schedule of each component in the maintenance program according to RBM. The expected duration of repair based on Table 6 is 380.124 hours, and the duration of maintenance based on Figure 9 is 1,200 hours. Thus, the availability level is 81.02%.

Table 6 Expected number of failures under RBM

Component	Expected number of failures
A	3.491
B	2.198
C	1.913
D	1.610
E	1.347

3.5. Integrated Maintenance Technique

The integrated maintenance technique is based on reliability, conditions, and risk. Components with high risk and low reliability become the maintenance priority. The integrated maintenance technique was developed to increase maintainability, such as through diagnostic improvement. This method has been used for a maintenance technique that integrates reliability, risk, and condition by using FDT (Failure of Defense Task), which has an MPI (Maintenance Prioritization Index) value and considers the condition monitoring (Pariaman et al., 2015b). As a result, the duration of maintenance or repair time is shortened from 240 hours (10 days) to 168 hours (7 days) for each component. For each additional component, the duration increases by 84 hours (3.5 days). For example, the maintenance for two components is 252 hours (10.5

days). Components A and C are the maintenance priorities of the considered system because each component has low reliability and a high-risk index. The maintenance schedule is designed based on the balance between low-reliability and high-risk components. Figure 10 shows the maintenance schedule for each component in the maintenance program. The expected duration of repair time based on Table 7 is 1,438.584 hours, and the duration of maintenance based on Figure 10 is 1,176 hours. Thus, the availability is 90.07%.

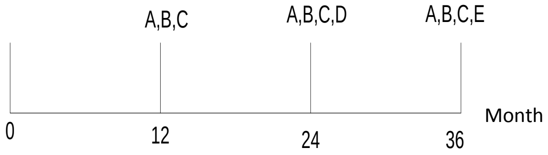

Figure 10 Integrated maintenance program

Table 7 Expected number of failures for integrated maintenance technique

Component	Expected number of failures
A	2.964
B	1.614
C	1.577
D	1.128
E	1.280

4. COMPARATIVE ANALYSIS

The availabilities were obtained based on several simulations that were executed on the same system. Table 8 shows a comparison of availabilities among the various considered maintenance techniques. It shows that the integrated maintenance technique provides the highest availability level compared to the other maintenance techniques.

Table 8 Comparison of availabilities

Maintenance technique	Availability level
Conventional	80.99 %
CBM	84.92 %
RCM	81.56 %
RBM	81.02 %
Integrated	90.07 %

The availability provided by each maintenance technique is impacted by the technique's maintenance program (i.e., activities and schedule). The integrated maintenance technique produces better availability than the other maintenance techniques primarily because the maintenance and repair durations are significantly shortened (Pariaman et al., 2015b).

5. CONCLUSION

In this paper, a mathematical model for calculating availability was presented. The RCM, CBM, RBM, and Integrated Maintenance techniques were simulated to determine the availability they respectively produce. The integrated maintenance technique considered reliability, condition, and risk. The results indicate that the integrated maintenance technique provides the highest availability. This study concludes that the integration of RCM, RBM, and CBM can result in increased system availability compared to the separate used of each maintenance technique. The availability simulation is assumed in only a series system and not a parallel system or combination of the two. This research uses the Weibull distribution for behavioral failure. Further research can be modelled by another distribution, such as a lognormal distribution.

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