Risk and reliability analysis on critical components of boiler in steam power plant

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Abstract. This paper uses the failure mode and effect analysis (FMEA) approach to conduct a risk analysis, and the reliability approach to determine the level of reliability of critical components of boiler sections in steam power plants. The critical components of the boiler will be identified failure modes, causes of failures and effects of failures, and then assess the severity, occurrence and detection to get a risk priority number (RPN). The critical boiler component with the highest risk is calculated for reliability. The results of this paper show the highest risk found in the four critical components of the boiler, namely cyclone separators, primary air fan (PA fan), coal feeder, and induced draft fan (ID fan). While the reliability calculation results of the four components, the average reliability value obtained is below fifty percent, or including low. The results of risk and reliability analysis that recommend to minimize risk and improve the reliability of critical components in the boiler using diagnostic methods, conducting preventive controls, using visual management techniques, using sensors to distinguish failures, and carrying out preventive and scheduled maintenance to prevent unexpected outages in the generating system.

1. Introduction
Steam power plants have an important role in the world electricity system. The majority of countries in the world still use steam power plants because of the relatively affordable production costs. Indonesia is one of the countries whose electricity production still relies on steam power plants. This business is operated by PT. Perusahaan Listrik Negara (PT. PLN) as a producer and manager of electricity in Indonesia, and owned by the Indonesian government in the form of a state-owned enterprises (SOEs). PT. PLN has many steam power plants in various regions in Indonesia, and one of its plants is located in Nagan Raya Regency. The Nagan Raya steam power plant has a 2x100 MW generating capacity. In its production system, Nagan Raya steam power plant has several important parts such as boilers, turbines, and generators.

The Nagan Raya steam power plant often fails in its production activities which results in unexpected system outages. Boilers are one of the parts that cause unexpected system outages because they often experience interference or damage. Interference or damage to the boiler has the highest frequency compared to other parts, such as generators and turbines. Boilers have several supporting components in their work systems, and are interrelated between components. Components that are often damaged can be said to be a critical component. Interference or damage to boiler critical components is caused more by maintenance systems that still use corrective maintenance.
Performance evaluation is needed, both in terms of reliability and risk arising from damage to critical components in the boiler.

The risk is a measure of the potential expected loss occurring due to natural or non-natural activities [1]. One method used to analyze the risk of damage is the failure mode and effect analysis (FMEA). FMEA is a vital reliability tool to identify critical failure modes, failure causes, and failure mechanisms that can be used to diagnose probable failure and dissatisfaction of functions for any items in a system before they occur, aiming to reduce their risks [2]. FMEA has been widely applied in various fields and is able to reduce risk [3-5]. Reliability is a measure of the ability of a component or equipment to operate continuously without interruption or damage [6]. Reliability can result from the uncertainty of the damage that occurs. Reliability will indicate the ability percentage of components that are often damaged or critical components. Previous studies have shown that reliability techniques are capable of describing actual engine performance, and are an evaluation material for increasing the effectiveness of engine performance [7-9]. In addition, the development of reliability techniques is also carried out by combining with simulations [10-12].

The purpose of this study is to analyze the risk and reliability of critical boiler components that have a high risk, so as to produce recommendations for future improvement.

2. Methods
This research was conducted at a steam power plant located in Nagan Raya Regency, Aceh Province, Indonesia. Components on the boiler that experience interference or damage will be the object of research. Figure 1 shows the stages carried out in the study, and displayed in the form of research flowcharts.
3. Result and Discussion

3.1. Boiler Specifications and Systems

Boiler is the object of this study because it has the highest frequency of damage among other parts. The boiler functions as a tool for producing high-pressure hot steam produced from coal combustion, which will then be used to drive turbines to produce electricity. The Nagan Raya steam power plant uses a boiler with the following technical specifications.

- **Brand**: Wuxi Huaguan Boiler Co, Ltd
- **Model**: UG-430/9.8-M
- **Steam Temperature**: 540°C
- **Steam Pressure**: 9.8 MPa
- **Product Number**: 09046
- **Manufacturing License**: TS2110520-2010

The Nagan Raya steam power plant in the combustion process uses a fluidizing bed boiler (CFB boiler). This boiler does not use a mill pulverizer, and the coal used is around 30 mm in diameter, and is equipped with a cyclone separator. The cyclone separator functions to separate fly-ash that is used to heat superheaters, economizers, and air heaters. Fly-ash will be discharged through the pile after
passing through an electrostatic precipitator to filter out exhaust gases that are harmful to the environment. Unburned fly ash particles will be returned to the furnace combustion chamber and used again to heat most superheaters, economizers, and air heaters. This type of boiler is also a type of kettle minus or has drawbacks because it only uses a induced draft fan without using a force draft fan. In addition induced draft fan, there are also primary air fan, secondary air fan and high pressure fluidizing air fan. Primary air fan functions as air which blows bed material so that a fluidization system occurs. Secondary air fan functions as air for combustion in the furnace. While the high pressure fluidizing air fan functions as an air flow to return the bed material carried to the cyclone separator to return to the furnace.

3.2. FMEA Result

The FMEA method is based on the discovery, regulation and reduction of failures or errors, and has been used in various types of industries [13]. FMEA can be used for energy production systems such as in steam power plants consisting of complex systems of mechanical and electrical components, in this case the boiler. FMEA uses three risk factors to identify failure modes, namely occurrence (O), detectability (D), and severity (S). Each risk factor will be indicated in the form of a Risk Priority Number (RPN). Three input parameters are rated on a 10-point scale. In this paper, sixteen boiler components that are frequently interrupted or damaged will be assessed using a risk priority number (RPN). Failure modes, causes of failures, and effects of boiler component failures will be identified first. Table 1 shows failure mode and effect analysis (FMEA) of boiler critical components, and Table 2 shows risk priority number (RPN) of boiler critical components.

| Component       | Failure Mode            | Cause Failure                                  | Failure Effect              |
|-----------------|-------------------------|------------------------------------------------|-----------------------------|
| Hopper          | Obstacles due to hopper ash | Lots of ash piled up                          | Hopper is stuck             |
| Conveyor        | Broken scraper conveyor | Coal overcapacity                              | Conveyor is stuck or not working |
| Coal Feeder     | Leakage on outlet flange | Coal stacking                                  | Coal feeder cannot operate  |
| Furnace         | High pressure furnace   | Insert the air heating element                  | High pressure steam heat    |
| Steam Drum      | Pipe level transmitter, outbreak of cladding | No visual inspection performed on the return leg | Solid particles accumulate in the fluid system |
| Cyclone Separator | Manhole u-beem           |                                               |                             |
| Desuperheater   | Bypass valve, outlet valve and control valve | The steam isn’t right | Turbine cannot operate |
| Economizer      | Drain pipe is leaking    | High pressure steam heat                       | Wasted heat                 |
| Downcomer       | Drain pipe is leaking    | High pressure steam heat as                    | Wasted heat                 |
| Sootblower      | Sootblower C30          | There is no visual inspection                  | Pile of dirt in the pipe    |
| Burner          | Burner trip             | Loss of flame, module flame is damaged, dirty flame scanner | Derating                    |
| Slag Cooler     | Leaking on the slag cooler | High pressure steam heat | Slag piled up               |
| Induced Draft Fan (ID Fan) | Air turbulence in the fan, unbalanced rotor | Valve opening does not comply with S.O.P, there is wear on the fan blades | High vibration |
| Primary Air Fan (PA Fan) | Air turbulence in the fan, unbalanced rotor | Valve opening does not comply with S.O.P, there is wear on the fan blades | High vibration |
Secondary Air Fan (SA Fan)  Air turbulence in the fan, unbalanced rotor  Valve opening does not comply with S.O.P, there is wear on the fan blades  High vibration

High Pressure Fluidized Air Fan  Air turbulence in the fan, unbalanced rotor  Valve opening does not comply with S.O.P, there is wear on the fan blades  High vibration

Table 2. Risk priority number (RPN) of boiler critical components

| No | Component                  | Severity | Occurrence | Detection | RPN  | Category |
|----|----------------------------|----------|------------|-----------|------|----------|
| 1  | Cyclone Separator          | 8        | 7          | 6         | 336  | High risk|
| 2  | Primary Air Fan (PA Fan)   | 6        | 6          | 9         | 324  |          |
| 3  | Coal Feeder                | 7        | 6          | 7         | 294  |          |
| 4  | Induced Draft Fan (ID Fan) | 5        | 7          | 8         | 280  |          |
| 5  | Desuperheater              | 8        | 5          | 6         | 240  | Moderate |
| 6  | Economizer                 | 8        | 6          | 5         | 240  |          |
| 7  | Furnace                    | 8        | 4          | 6         | 192  |          |
| 8  | Steam Drum                 | 8        | 4          | 5         | 160  |          |
| 9  | Sootblower                 | 8        | 4          | 5         | 160  |          |
| 10 | Slag Cooler                | 7        | 3          | 7         | 147  | Low risk |
| 11 | Downcomer                  | 7        | 3          | 7         | 147  |          |
| 12 | Conveyor                   | 8        | 3          | 6         | 144  |          |
| 13 | Burner                     | 6        | 4          | 5         | 120  |          |
| 14 | Hopper                     | 5        | 3          | 7         | 105  |          |
| 15 | Secondary Air Fan (SA Fan) | 5        | 4          | 5         | 100  |          |
| 16 | High Pressure Fluidized Air Fan | 4 | 3 | 6 | 72 | Low risk |

After evaluating RPN, the highest value is clearly seen in Figure 2. The sixteen components are the main concern given the high impact that can occur on the steam power plant, especially on the boiler if the component fails. The next step is to analyze the FMEA output, where the failure mode depends on the severity, occurrence, and detection. RPN is categorized into three levels of risk, namely low risk (1-149), moderate risk (150-249), and high risk (250-340). FMEA output analysis will be performed on several components of boiler sections that have a high risk or high critical level, such as coal feeder, cyclone separator, induced draft fan (ID fans), and primary fan (PA fans). This issue must be considered to reduce the risk to the steam power plant system. Figure 2 shows the highest to lowest RPN in each critical component of the boiler section.
3.3. Risk Analysis

Risk analysis is one of the most rational methods for identifying failure modes in a steam power plant, especially in the boiler section. The risk analysis using FMEA is an approach to prioritize the potential risk according to the failure causes [14]. In this risk analysis, the boiler has sixteen pieces of equipment that often experience interference or damage, and there are at least 4 components that have the highest RPN value so that it can be categorized as a critical component. The highest RPN value was obtained on a cyclone separator with RPN 336. The other highest RPNs are primary air fan (PA fan), coal feeder and induced draft fan (ID fan) with RPN values 324, 294 and 280.

Figure 2 illustrates the gap that occurs in each important boiler component. It seems that all four components have the highest RPN compared to other components, and the gap looks significant based on Figure 2. Some recommendations can be applied to reduce the risk of damage to boiler components, namely using diagnostic methods, conducting preventive controls, using visual management techniques, using preventive maintenance to develop them towards simulations to predict failure or damage, using sensors to distinguish failures, and developing inspection methods to identify unexpected failures on certain equipment.

3.4. Reliability Result

The reliability calculation is performed on four important components for the two boiler units owned by the Nagan Raya steam power plant. The four critical components are the cyclone separator, primary air fan (PA fan), coal feeder and induced draft fan (ID fan). Failure data used is from March 2015 to August 2015 (six months). The number of failures for each important component can be seen in Figure 3.
The first stage of the reliability calculation is the distribution test (index of fit) and parameter determination (goodness of fit), which is carried out at the time to failure (TTF) and time to repair (TTR) of each important component in the boiler. Calculations using the Minitab 16 program. The chosen distribution will use two assessment methods, namely Anderson Darling (AD) and the Pearson correlation coefficient. While the parameters are determined based on the distribution that has been previously selected. Recapitulation of distribution and parameters tests for time to failure (TTF) and time to repair (TTR) for each boiler critical component using the Minitab 16 program, can be seen in Table 3 and Table 4.

**Table 3. Recapitulation of distribution and parameters test for time to failure (TTF).**

| Boiler | Component       | Distribution | Parameter       | Weibull | Normal |
|--------|-----------------|--------------|-----------------|---------|--------|
|        | Cyclone Separator | 3p-Weibull  | Θ  | β   | γ  | μ  | Σ  |
| Unit 1 | Coal Feeder     | 3p-Weibull  | 369.225 | 0.43689 | 328.300 | - | - |
|        | ID Fan          | 3p-Weibull  | 390.156 | 0.36609 | 330.634 | - | - |
|        | PA Fan          | 3p-Weibull  | 263.237 | 0.28650 | 333.260 | - | - |
|        | Cyclone Separator | Normal  | - | - | - | 694.402 | 364.251 |
| Unit 2 | Coal Feeder     | 3p-Weibull  | 338.177 | 0.66965 | 321.707 | - | - |
|        | ID Fan          | 3p-Weibull  | 487.349 | 0.64880 | 311.411 | - | - |
|        | PA Fan          | 3p-Weibull  | 161.367 | 0.20106 | 334.064 | - | - |

**Table 4. Recapitulation of distribution and parameters test for time to repair (TTR).**

| Boiler | Component       | Distribution | Parameter       | Weibull |
|--------|-----------------|--------------|-----------------|---------|
|        | Cyclone Separator | 3p-Weibull  | Θ  | β   | Γ  |
| Unit 1 | Coal Feeder     | 3p-Weibull  | 0.86862 | 0.39684 | 1.01595 |
|        | ID Fan          | 3p-Weibull  | 0.96547 | 1.61950 | 0.97137 |
|        | PA Fan          | 3p-Weibull  | 0.73507 | 0.64297 | 1.08582 |
|        | Cyclone Separator | 3p-Weibull  | 0.81565 | 1.42279 | 0.89147 |
After the distribution and parameters from time to failure (TTF) and time to repair (TTR) for each critical boiler component are obtained, the next step is to determine the mean time to failure (MTTF), mean time to repair (MTTR) and reliability. Examples of MTTF calculations for cyclone separator unit 1 is as follows.

\[
MTTF = \gamma + 0.\Gamma \left( 1 + \frac{1}{\beta} \right)
\]

\[
MTTF = 328.300 + 369.225 \times \Gamma \left( 1 + \frac{1}{0.43689} \right)
\]

\[
= 328.300 + 369.225 \times \Gamma(3.29)
\]

\[
= 328.300 + 369.225 \times 1.97565 = 1,057.76 \text{ hours}
\]

Examples of reliability calculations for cyclone separator unit 1 is as follows.

\[
R(t) = e^{-\left( \frac{t}{\theta} \right)^{\beta}}
\]

\[
R(t) = \exp \left[ -\left( \frac{1,057.76 - 328.300}{369.225} \right)^{0.43689} \right] = 0.4218 = 42.18% 
\]

The recapitulation of the calculation results from MTTF, MTTR and reliability of boiler critical components can be seen in Table 5.

| Boiler | Component       | MTTF (Hours) | Reliability | MTTR (Hours) | Reliability |
|--------|-----------------|--------------|-------------|--------------|-------------|
| Unit 1 | Cyclone Separator | 1,057.76    | 42.18%      | 2.95        | 41.39%      |
|        | Coal Feeder     | 1,292.40    | 40.56%      | 1.84        | 23.43%      |
|        | ID Fan          | 1,238.91    | 37.32%      | 2.11        | 40.97%      |
|        | PA Fan          | 866.82      | 41.30%      | 1.63        | 27.45%      |
| Unit 2 | Cyclone Separator | 694.40      | 50.00%      | 1.67        | 40.16%      |
|        | Coal Feeder     | 805.17      | 38.39%      | 1.60        | 32.79%      |
|        | ID Fan          | 978.00      | 41.17%      | 2.10        | 41.03%      |
|        | PA Fan          | 1,260.74    | 31.52%      | 1.71        | 39.66%      |

3.5. Reliability Analysis

After calculating the reliability of four critical components, namely cyclone separator, primary air fan (PA fan), coal feeder and induced draft fan (ID fan), the average reliability value obtained is below fifty percent, or including low. The results of the calculation of the mean time to failure (MTTF), showed the maintenance interval is 694 hours to 1,292 hours with a reliability of 31% to 50%. While the results of the calculation of the mean time to repair (MTTR), showed the repair interval is 1.60 hours to 2.95 hours with a reliability of 23% to 41%. The low reliability value is caused by the
maintenance system implemented by the Nagan Raya steam power plant which still uses corrective maintenance. In addition, the reliability of the machine is also influenced by the age of use, the longer the service life the more damage will occur. To increase the value of reliability, preventive maintenance can be carried out so that maintenance time can be well scheduled. Scheduled maintenance also prevents unexpected outages in the generating system.

4. Conclusion
The results of risk assessment on critical components of the boiler using failure mode and effect analysis (FMEA), the highest risk was found in four critical components, namely cyclone separator, primary air fan (PA fan), coal feeder and induced draft fan (fan ID). While the reliability calculation results of the four components, the average reliability value obtained is below 50%, or including low. The results of risk and reliability analysis that recommend to minimize risk and improve the reliability of critical components in the boiler using diagnostic methods, conducting preventive controls, using visual management techniques, using sensors to distinguish failures, and carrying out preventive and scheduled maintenance to prevent unexpected outages in the generating system.

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