Pertanika J. Sci. & Technol. 28 (S1): 69 - 81 (2020)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Intelligent Risk-Based Maintenance Approach for Steam Boilers: Real Case

Noor Fazreen Ahmad Fuzi[1], Firas Basim Ismail Alnaimi[1]* and Mohammad Shakir Nasif[2]

[1]Power Generation Unit, Institute of Power Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia
[2]Department of Mechanical Engineering, Universiti Teknologi Petronas (UTP), 32610 Seri Iskandar, Perak, Malaysia

ABSTRACT

Maintenance acts as a significant role in smoothening the operations in power plants. Risk and failure are some of the common problems in power plant leading to unexpected outages such as boiler shutdown or tube leakage. The rectification of these problems requires ceasing operations of the boiler which leads to a loss in the revenue annually. Therefore, this work was focused on prioritizing the maintenance activities and optimize the operational duration and cost by implementing risk-based maintenance (RBM) and particle swarm optimization (PSO). Previous literature implores that, RBM is commonly used in oil and gas industries to predict the risk or failure of the equipment. In this work, the RBM method was adopted accordingly to the power plant industries. The methodology is segregated into two main phases. First, the ranking and prioritization maintenance activities were performed using RBM. Then, the optimization of the operational duration and cost were simulated by PSO approached in MATLAB. The main outcome of this research is to act as a reference in adopting the best approaches to improve the power plant performance.

Keywords: Maintenance scheduling, optimization, particle swarm optimization, risk-based maintenance, steam boiler

ARTICLE INFO

Article history:
Received: 26 February 2020
Accepted: 18 May 2020
Published: 16 September 2020

E-mail addresses:
fazreen143@gmail.com (Noor Fazreen Ahmad Fuzi)
Firas@uniten.edu.my (Firas Basim Ismail Alnaimi)
mohammad.nasif@utp.edu.my (Mohammad Shakir Nasif)
*Corresponding author

INTRODUCTION

Power generation in Malaysia is dominated by two main types of energy source which are thermal power plant and hydropower

ISSN: 0128-7680
e-ISSN: 2231-8526

plant. Thermal power plants generate power using conventional steam turbines and steam generators with coal, oil or natural gas as fuels. Thermal plants can be further classified as a steam power plant, open cycle gas turbine generators (gas-fired or diesel-fired), and combined cycle turbine generators (gas-fired or diesel-fired). The selection of coal as fuel is according to a five-fuel policy to reduce heavy dependence on natural gas (Tenaga Nasional Berhad, 2018).

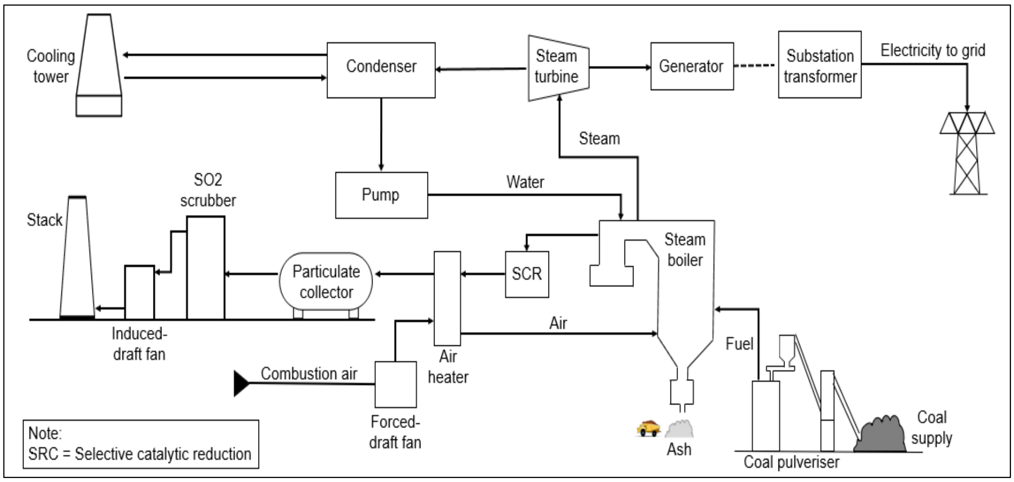

Figure 1. The revised version of the thermal power plant schematic diagram (Kubota, 2015)

In a plant, each major component plays a key role to ensure that the power plant operates efficiently. The components consist of a steam boiler, steam turbine, furnace and chimney (Kubota, 2015). In this work, the steam boiler is identified as the most crucial component due to major outage and the highest incurring maintenance cost. Steam boiler commonly known as the steam generator is shown in Figure 1, which is the most complex industrial component which involved the nonlinear, phase-change and inverse-response performance and also operated as a significant machinery in modelling and simulation challenge (Sunil et al., 2014). Boiler shortage and unexpected shut down incur heavy loss revenue and can further damage other components (Zhakiyev et al., 2017). Therefore, each component must be maintained according to the schedule.

Scheduled maintenance or preventive maintenance is the most common maintenance strategy implemented in industries. Preventive maintenance (PM) is a time-based maintenance method where the maintenance is planned and scheduled to optimize failure during the operation. PM is broadly used specifically for ageing equipment (Borikar et al., 2014; Dachyar et al., 2018). In this work, schedule maintenance for the steam boiler was analyzed to identify the highest expenditure in maintenance cost. The overhaul maintenance process consumes the longest maintenance operational duration which leads to the highest maintenance cost. The overhauling process is a time-consuming operation that includes three phases which are cleaning, repairing and testing. The overhaul is expected to be completed in 35 to 40 days estimated duration (Chandra et al., 2011).

According to Anderson (2015), 80% of preventive maintenance cost is spent on maintenance activities which running within 30 days or less and 30% to 40% of the preventive maintenance cost is spent on unnecessary failure. These are due to the factors such as the inefficient maintenance process, ageing equipment and also redundancy maintenance task which lead to the repetition that takes longer maintenance duration (Ge, 2010; Wang, 2018). To overcome this problem, this work analyzed the Multi-Criteria Decision Making (MCDM) which is a method that is widely adopted to decide on the prioritization maintenance schedule. MCDM consists of Analytical Hierarchy Process (AHP), Failure Mode and Effect Analysis (FMEA), and Risk-Based Maintenance (RBM). RBM is used widely in the oil and gas industry. However, in the previous study, the research works did not cover maintenance scheduling specifically for thermal power plants. Most of the previous studies concentrated on one of the aspects of the risk assessment of such pipes and the possibility of failures in the oil and gas industry. Thus, based on the literature review, this work would be implementing the RBM for maintenance scheduling in the thermal power plant.

Maintenance is crucial to manufacturing operations as wear and tear over time of moving parts is an absolute certainty. In many times the facilities and the production equipment represent the majority of invested capital and deterioration of these equipment increases production cost and reduces the production quality. Preventive maintenance is scheduled to prevent breakdown and equipment deterioration. However, to maximize return on their equipment investment managers attempt to identify the risky equipment required time interval between preventive maintenance action which will balance the cost of breakdowns and equipment deterioration. The risk-based maintenance system identifies critical equipment based on risk evaluation. Overall equipment and component maintenance plans are carried out to reduce the risk of the operation. By pre-scheduling the maintenance activities, RBM approaches the consequences of failures and downtime and reduces it to a minimum level for which the criteria considered are set up financial risks (Sarkar & Behera, 2012; Hameed, 2016).

Based on Khan and Abbasi (1998, 2000), the major challenge for the maintenance engineer is to implement a maintenance strategy based on four criteria which are maximizing the equipment availability and efficiency, controlling the deterioration rate of the equipment, ensuring safe and environment-friendly operation and optimize the total cost of the operation. The only action can be taken is by adopting a structured approach to the study of the equipment. Nowadays, Khan and Haddara (2003) suggested an improvised risk-based inspection and maintenance approach. The new approach was adopted with a specific case study. This method integrates significant risk assessment with proven reliability analysis approaches. The prioritization of the equipment is based on the total risk in terms of economic, safety and environment. Scheduling maintenance is enhanced to optimize the inadequate risk.

Nowadays, the maintenance planning problem is a common problem, especially in the power generation industry. As for Evrencan et al. (2019), the maintenance planning problem was handled by considering risk evaluation to schedule effectively. By implementing Analytical Hierarchy Process (AHP) hybrid with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the result then was validated using the RBM model to ensure that the risk is reduced. Besides, Cullum et al. (2018) were implementing RBM to reschedule the maintenance activities for naval vessels and ship. This implementation aimed to reduce the maintenance cost and meeting the availability requirements.

The risk priority number ranking was once introduced in the Failure Mode and Effect Analysis (FMEA) method. However, due to the traditional FMEA, the risk analysis suffered from major weaknesses. Nowadays, RPN ranking had been used widely by the researcher by merging with the RBM method which is more reliable compared to the independent RPN. RPN is engineered to identify the existing and potential risk or failures either in design, process or planning maintenance before they occur, and prevent the undesirable incidents thus protecting the employees from the occupational accidents and diseases by taking the necessary measures (Jamshidi, 2017; Setiawan et al., 2017; Stamatis, 1995).

In recent years, the growth of the evolutionary theory development, such as the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) have grown into effective optimization tools and implemented widely in power engineering applications. PSO is a mathematical optimization algorithm that was initiated by Kennedy and Eberhart (1995). It has been successfully adopted into problems such as artificial neural network training, function optimization, fuzzy system control, and pattern classification and more (Chu et al., 2006, Samuel & Rajan, 2015). To be highlighted, the main objective of this research was optimizing the maintenance scheduling and form the new list of maintenance activities. Based on the new list of maintenance activities, the operational time and cost would be minimized and the productivity of the worker is increased.

METHOD

The risk-based maintenance (RBM) procedure is a mechanism to plan an effective maintenance scheduling with minimal expected failure of the machine. A simplified RBM procedure is illustrated into Figure 2. The outcome of this RBM method is to enhance the reliability of the equipment and optimizes the total maintenance cost. The equation below is a common problem-solving in the RBM procedure.

$$Risk = Probability\ of\ Failure \times Consequences\ of\ Failure$$

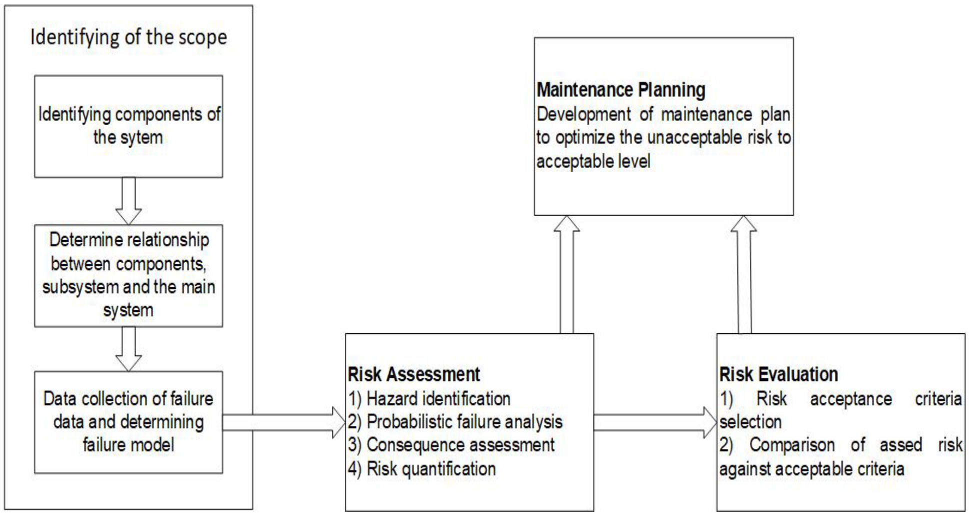

Figure 2. RBM Methodology

Identification of the Scope

The data used in this work was collected from the adopted thermal power plant with a generating capacity of 210MW. Every thermal power plant had similar components as shown in Figure 1. However, the steam boiler is always the key facility in the power plant as it is producing steam to generate electricity. Based on this power plant, the steam boiler consists of six main components which are boiler pressure parts, boiler drum, air preheater, safety valve, heat pressure valves, and coal and oil burner system.

Based on the literature review (Damodar Corporation, 2009), the overhauling process is the most critical maintenance activities in most of the steam boiler power plant. The overhauling process requires the whole system to be shut down in an estimated 35 to 40 days. For this work, the overhaul process for the drum boiler was selected to be implemented in the RBM model (Table 1). To be highlighted, this research only focused on the ranking and prioritization of the maintenance activities according to the risk of failure.

Table 1
Maintenance activities for overhaul boiler drum (Damodar Corporation, 2009)

No	Maintenance activities
M1	Disclosed the boiler drum manholes and accommodate with an exhaust fan to allowed cooling. The contractor will modify the fan accordingly. Cover the downcomer with covers and asbestos cloth.
M2	24 volts power supply connection is required when working inside the drum. (Required transformer from 220V input to be arranged by the contractor).
M3	The cyclone separator in the drum internal is removed for inspection.

Table 1 *(Continued)*

No	Maintenance activities
M4	Wash the welding joints of steam chest, cyclone separator using Teflon brush to avoid the magnetite layer destruction.
M5	The drum internals is inspected.
M6	The DPT of the welding joints of the steam chest is done after cleaning. The contractor is in charge of DPT and will be inspected by a DVC representative.
M7	The drum's phosphate dosing header is taken out and clean it effectively.
M8	Then, re-welding the header in its position.
M9	Removed the CBD isolation v/v bonnet or rip the CBD line to avoid any chocking.
M10	Welding of CBD line and phosphate dozing line shall be carried out by HP welders only. No extra payment will be made for cutting/welding of CBD or phosphate dosing lines.
M11	Wash and blue matching the drum manholes and counter surface. (Material build-up and scrapping to be carried out to complete the matching surface if required)
M12	Gather the drum internals and remove all the left-out materials.
M13	Engineer In-charge inspected. The drum is enclosed after putting a suitable gasket for the drum manhole.
M14	Hot tightening proceeds after boiler light-up at pressures required by the EIC.
M15	The downcomer suspension and drum suspension is checked.

Risk Assessments

Risk assessment is started by identifying the probability of risks from each failure scenario that may occur in the future. The Risk Priority Number (RPN) model is modeled based on the below equation in the Excel file to measure and identify the most critical based on the survey forms that been distributed to the maintenance team.

$$RPN = S\ X\ O\ X\ D$$

Where S is severity where an estimation of how severe the customer will discover the effect of a failure. O is an occurrence where a numerical estimation on the cause of a failure mode will happen within the design phase. D stands for detection where it is an estimation in numerical is made to prevent the cause of failure from occurs before delivery to the customer.

From the value of calculated RPN, the failure mode is ranked individually from high to low risk respectively. The scheduling of the RPN will prioritize the maintenance task to reduce and limit the failure occurrence. To be noted, the calculated RPN is not an absolute value but a respective value. Lastly, it is also able to present the initial state of risk assessment according to the assumption. Based on the predicted maintenance, the maintenance team is assigned to analyze scenarios separately to determine and analyze the impact of the higher risk in RPN, thus it will help to reduce the operational risk of those predicted failure modes.

Risk Evaluations

An adequate risk criterion is studied and determined either the risk of each failure scenario is adequate or not. Failure scenarios that form inadequate risk are used to determine maintenance policies for the components involved. To calculate the RPN, a ranking table for the occurrence, severity, and detection are tabulated as follows.

Table 2
Ranking RPN calculation values for S, O, and D (Setiawan, 2017; Jamshidi, 2017)

Descriptions	RPN value
Occurrence (O)	
Definite (More than 50 times/year)	10
Very possible (10 times/year)	7
Possible (1 times/year)	5
Impossible (1 times/3 year)	3
Almost impossible (1 times/5 year)	1
Severity (S)	
Definite (More than 50 times/year)	10
Very possible (10 times/year)	7
Possible (1 times/year)	5
Impossible (1 times/3 year)	3
Almost impossible (1 times/5 year)	1
Detection (D)	
More than 10 years not detectable	10
Within 5 years	7
Within a year	5
Within half-year	3
Direct detection (e.g. signal to control centre)	1

Maintenance Planning

Failure sub-systems are studied to restructure an optimizing risk maintenance program. The maintenance type and maintenance duration are determined during this phase. In this research, the maintenance interval is used only to reduce the failure probability. When the maintenance interval is modified, the risk failure probability will also be affected. An RPN model is used to prioritize maintenance activities based on the probability and consequences of failure. Consequence analysis involving the total cost of estimation maintenance and the production loss. Following equation is the calculation of the maintenance cost (MC):

$$MC = C_f + D_t \, X \, C_v$$

C_f is the failure fixed cost (e.g. spare parts cost), D_t is the downtime and C_v is the variable cost per hour of shutdown (e.g. manpower cost). Downtime maintenance is the total duration of the plant to be out of service starting from the moment of fails until the moment it is back to operation. While to calculate production loss cost (PLC), the equation is as follow:

$$PLC = D_t \, X \, PL \, X \, SP$$

D_t is the downtime, PL is the production loss in Megawatt, and SP is the generated electricity selling price. The manpower cost is the main cost to be considered in the maintenance cost. The hourly rate depends on the industry. The downtime process is usually related to the forced outage and forced de-rating state. This process is estimated from the historical failure data from the power plant. Due to the lack of data, this research only presents the ranking and prioritization of the maintenance activities by implementing into RPN model (Arunraj & Maiti, 2007; Khan et al., 2011; Mehairjan, 2016).

RESULTS AND DISCUSSION

Rank and Prioritize Maintenance Scheduling using Risk Priority Number (RPN)

Higher accuracy of results can be obtained using RPN method instead of Bayesian Network or Fault Tree Analysis. Based on the previous studies, the RPN method is more reliable for unmeasurable data (Khakzad et al., 2011). For each identified failure mode, the RPN value is calculated in the Excel model. An assessment of these maintenance activities by calculating the RPN value by substituting the ranking value from Table 2 was implemented into equation RPN to optimize the consequence of a specific failure mode. The results are tabulated as shown in Table 3. The results are shown as follows.

$$RPN = 8 \, X \, 10 \, X \, D = 400$$

Table 3
Results of RPN values

Maintenance	RPN value	RPN value (%)
M1	400	40.0
M2	8	0.8
M3	48	4.8
M4	315	31.5
M5	36	3.6
M6	24	2.4
M7	125	12.5
M8	27	2.7
M9	60	6.0
M10	240	24.0
M11	75	7.5
M12	18	1.8
M13	18	1.8
M14	18	1.8
M15	18	1.8

Based on the result obtained, the new maintenance scheduling is corresponding to the risk failure and criticality of each activity. From Figure 3, the results show that M1 (40%) is the most critical with respect to the severity and occurrence, followed by M4 (31.5%), M10 (24.0%), M7 (12.5%), M11 (7.5%), M9 (6.0%), M3 (4.8%), M5 (3.6%), M8 (2.7%), M6 (2.4%), M12 (1.8%), M13 (1.8%), M14 (1.8%), M15 (1.8%), and M2 (0.8%). The new maintenance activities were rearranged descendingly. As for M12 to M15 which produced identical values, it was rearranged based on the S values as it was the most critical compared to O and D values.

The new maintenance activities are verified by comparing the result obtained using the Analytical Hierarchy Process (AHP) method shown in Figure 4. A similar simulation had been simulated using AHP in Excel with the same parameters (severity, occurrence, and detection) and forming a similar ranking. This AHP method is used to verify the new maintenance activities forming by the RBM is effective and reliable. It is clear that the result is engineered according to the adopted thermal power plant and will be different if applied to other operation data.

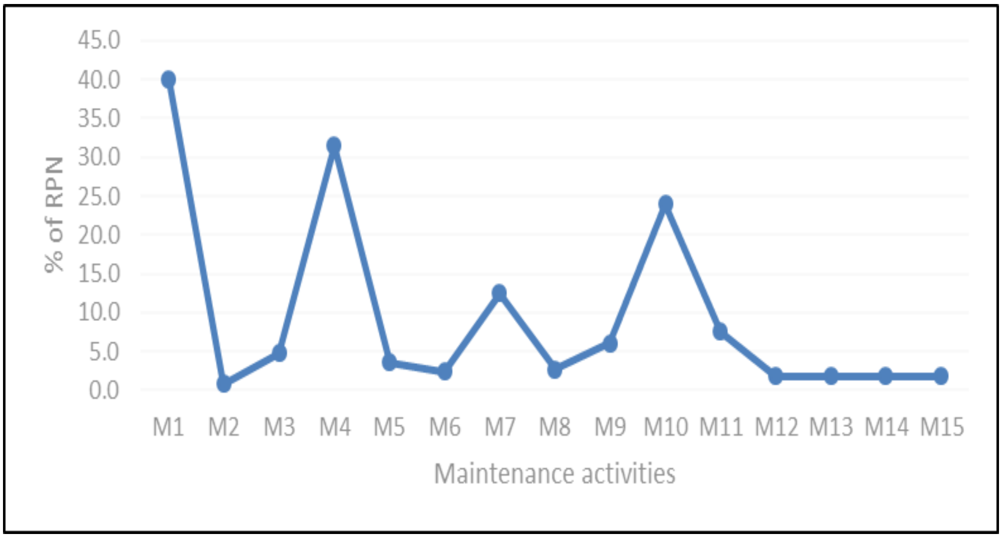

Figure 3. Illustration of ranking and prioritization maintenance activities based on the RPN values

AHP		
840	84.0%	1
20	2.0%	15
100	10.0%	7
700	70.0%	2
80	8.0%	8
50	5.0%	10
300	30.0%	4
60	6.0%	9
200	20.0%	6
600	60.0%	3
242	24.2%	5
42	4.2%	11
42	4.2%	12
42	4.2%	13
42	4.2%	14

Figure 4. Risk evaluation using AHP method as validation

CONCLUSION

This research proposed a procedure in rescheduling the preventive maintenance schedule based on minimizing the risk of failure. This approach was found to increase the safety of the equipment and minimize the maintenance cost. This will contribute to reduce plant shutdowns and ensure smooth and safe operations. In the methodology section, a new maintenance list is formed. The new maintenance scheduling is based on the risk in terms of severity, occurrence, and detection of the failure in maintenance. The new maintenance list is presented as M1 > M4 > M10 > M7 > M11 > M9 > M3 > M5 > M8 > M6 > M12 > M13 > M14> M15 > M2. The advantages of implementing the RBM are the reliability of the systems which is the steam boiler drum is enhance by using effective maintenance activities. Other than that, the RPN calculation is applicable to be used for maintenance activities as it will become possible to evaluate the costs and risks.

The present approach focuses only on the ranking and prioritization of maintenance activities due to the lack of data. However, in future work, the consequence analysis will be added after data collection. The consequence analysis will be analyzed and compared with the value obtained using particle swarm optimization and genetic algorithm. To conclude, by adopting and implementing the RBM modeling, risk failure probability from the maintenance schedule can be optimized and thus producing an effective maintenance scheduling. RBM can be adopted to evaluate the existing maintenance scheduling by using the risk management decision-making process of the systems to achieve the main objective.

ACKNOWLEDGEMENT

The authors would like to express gratitude to Power Generation Unit, Institute of Power Engineering (IPE), Universiti Tenaga Nasional (UNITEN), and Tenaga Nasional Berhad (TNB) for providing a research grant to carry out this research.

REFERENCES

Anderson, D. (2015). Reducing the cost of preventive maintenance. *Maintenance Journal, 15,* 1-14.

Arunraj, N. S., & Maiti, J. (2007). Risk-based maintenance – Techniques and applications. *Journal of Hazardous Materials*, *142*(3), 653-661.

Borikar, A., Shingare A., Sarnaik, J., & Bhusari, A. (2014). Implementation of total productive maintenance on boiler. In *International Conference on Advances in Engineering & Technology* (pp. 34-38). Singapore.

Chandra, A., William, M., Ricci, K. (2011). *Characterizing the U.S industrial base for coal-powered electricity*. Retrieved October 12, 2018, from https://www.rand.org/content/dam/rand/pubs/monographs/2011/RAND_MG1147.pdf

Chu, S. C., Chen, Y. T., & Ho, J. H. (2006, August 30 – September 1). Timetable scheduling using particle swarm optimization. In *First International Conference on Innovative Computing, Information and Control-Volume I (ICICIC'06)* (Vol. 3, pp. 324-327). Beijing, China.

Cullum, J., Binns, J., Lonsdale, M., Abbassi, R., & Garaniya, V. (2018). Risk-based maintenance scheduling with application to naval vessels and ships. *Ocean Engineering*, *148*, 476-485.

Dachyar, M., Nurcahyo, R., Tohir, Y. (2018). Maintenance strategy selection for steam power plant in range of capacity 300-625MW in Indonesia. *ARPN Journal of Engineering and Applied Sciences, 13*(7), 2571-2580.

Damodar Corporation. (2009). *Tender documents: Major overhauling of boiler and auxiliaries equipment of unit no. 4.* Damodar Valley Corporation Mejia Thermal Power Station, India. Retrieved October 20, 2018, from https://www.scribd.com/document/40789524/Major-Overhauling-of-Boiler-and-Auxiliaries-of-U-4-1

Evrencan, O., Yumusak, R., & Eren, T. (2019). Risk-based maintenance in the hydroelectric power plant. *Energies, 12* (8), 1-22.

Ge, H. (2010). *Maintenance optimization for substation aging equipment*. (Electrical Engineering Theses and Dissertations). University of Nebraska-Lincoln, USA.

Hameed, A. (2016). *Risk-based shutdown inspection and maintenance for a processing facility*. (Doctoral dissertation). Memorial University of Newfoundland, Canada.

Jamshidi, A. (2017). *Risk-based maintenance of critical and complex systems*. (Doctoral dissertation). Université Laval, Canada.

Kennedy, J. A., & Eberhart, R. C. (1995, October 4-6). A new optimizer using particle swarm theory. In *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science* (pp. 39-43). Nagoya, Japan.

Khakzad, N., Khan, F., & Amyotte, P. (2011). Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. *Reliability engineering and System Safety, 96*, pp. 925-32.

Khan, F. I., & Abbasi, S. A. (1998). *Risk assessment in chemical process industries: Advanced techniques*. New Delhi, India: Discovery Publishing House.

Khan, F. I., & Abbasi, S. A. (2000). Analytical simulation and PROFAT II: A new methodology and a computer automated tool for fault tree analysis in chemical process industries. *Journal of Hazardous Materials*, 75, 1-27.

Khan, F.I., & Haddara, M. R. (2003). Risk-based maintenance (RBM): A quantitative approach for maintenance/ inspection scheduling and planning. *Journal of Loss Prevention in the Process Industries, 16*, 516-73.

Khan, F. I., Rahman, M. S., Shaikh, A., Ahmed, S., & Imtiaz, S. (2011). Development of risk model for marine logistics support to offshore oil and gas operations in a remote and harsh environment. *Ocean Engineering, 174*, 125-134.

Kubota, H. (2015). *Case study: The Manjung 4&5 coal-fired power stations in Malaysia – similarities and differences*. Retrieved September 27, 2018, from https://docplayer.net/43367478-Case-study-the-manjung-4-5-1-000mw-ultra-supercritical-coal-fired-power-stations-in-malaysia-similarities-and-differences.html with verification from Jana Manjung power plant

Mehairjan, R. P. Y. (2016). *Risk-based maintenance in electricity network organizations*. (Master Thesis). Delft University of Technology, the Netherlands.

Samuel, G. G., & Rajan, C. C. A. (2015). Hybrid: Particle Swarm Optimization-Genetic Algorithm and Particle Swarm Optimization – Shuffled Frog Leaping Algorithm for long term generator maintenance scheduling. *International Journal of Electrical Power and Energy System, 65*, 432-442.

Sarkar, A., & Behera, D. K. (2012). Development of Risk-Based Maintenance Strategy for Gas Turbine Power System. *International Journal of Advanced Research in Engineering and Applied Sciences, 1*(2), 20-38.

Setiawan, T. H., Adryfan, B., & Putra, C. A. (2017). Risk analysis and priority determination of risk prevention using failure mode and effect analysis method in the manufacturing process of hollow core slab. *Procedia Engineering. 171*, 874-881.

Stamatis, D. H. (1995). *Failure mode and effect analysis*. Milwaukee, USA: ASQC Quality Press.

Sunil, P., Barve, J., Nataraj, P. (2014). Boiler model and simulation for control design and validation. *IFAC Proceedings Volumes, 47*(1), 936-940.

Tenaga Nasional Berhad. (2018, September 12). Business. Retrieved September 12, 2018, from https://www.tnb.com.my/about-tnb/our-business/#

Wang, W., Wu, Z., Xiong, J., Xu, Y. (2018). Redundancy optimization of cold-standby systems under periodic inspection and maintenance. *Reliability Engineering and System Safety, 180*, 394-402.

Zhakiyev, N., Akhmetbekov, Y., Silvente, J., & Kopanos G. (2017). Optimal energy dispatch and maintenance of an industrial thermal combined heat and power plant in Kazakhstan. *Energy Procedia, 142,* 2485-2438.