Analysis and Preventive Maintenance of Gas Engines in Gas Engine Power Plants

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Abstract

This study aims to determine the level of reliability of the gas engine, the root cause of the problem, and propose the implementation of preventive maintenance. Conduct this research on a company that provides electricity to the community. The research method uses Mixed Method with descriptive research type. The analytical tools used are MTBF, MTTR, DMAIC, with supporting methods in Root Cause Analysis and Why-why Analysis. The MTBF and MTTR calculations show that many MTBF and MTTR values do not reach the target. The root causes of downtime problems include dust and dirt—implementation of preventive maintenance including Maintenance Schedule. Thus the company needs to measure Gas Engine Reliability with MTBF, MTTR, root causes of problems with DMAIC, and Preventive Maintenance to reduce downtime in the future.

Keywords
DMAIC, MTBF, MTTR, Root Cause & Why-why Analysis

1. Introduction
The level of electricity consumption in Indonesia continues to show significant progress every year. In 2016 Indonesia's electricity consumption reached 956 kWh per capita. Meanwhile, in 2018, electricity consumption in Indonesia has born at 1,064 kWh per capita. Investors also saw strong support from the government (Akhir, 2019). Based on data published by the Investment Coordinating Board (Badan Koordinasi Penanaman Modal/BPKM), the number of investments in the second quarter of 2019, the largest sector of foreign investment in the second quarter of 2019 was in the electricity, gas, and water business sector with an investment of US$ 1.4 billion. Electrical energy needs to be generated, and how to create electrical power is currently quite expensive. Electrical energy cannot run out and cannot increase, as the law of energy conservation (BKPM, 2019).

In today's competitive market, productivity and quality have an important role for the company to compete among each other (Kang et al., 2016). According to Heizer et al. (2020), the breakdown of the machine can disrupt the company's productivity. In order for the company can run well, maintenance is very crucial, where one type of approach is called as Total Productive Maintenance (TPM). TPM is an equipment maintenance plan widely used in the manufacturing industry to reduce losses in production activities, extend equipment life, and ensure the effective use of equipment (Xiang & Feng, 2021).

This research was conducted on companies engaged in Gas Engine Power Plants, where this company meets the electricity supply needs in Indonesia, especially in the Riau Islands. The company was established in 2015 with the company's location in Batam, Riau Islands region. The problem experienced by the company is a breakdown or damage to the gas engine, resulting in downtime (the time the gas engine does not operate), where the gas engine is expected to operate 24 hours a day without a breakdown. From January 2018 to July 2019, among three gas engines, the average monthly breakdown is 96 hours for machine 1, 95 hours for machine 2, and 77 hours for machine 3 with a downtime tolerance of 38 hours per month at the time off of work inspection. The impact due to downtime that causes electricity production per day that is not optimal will result in wasted electricity and a penalty that the company should pay to the customer.

Based on previous research conducted by Lomte et al. (2018), the problem in their research is the breakdown that causes downtime on the Twin Screw Roller (TSR) machine. To overcome this, they used the calculation of Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) to determine the value of MTBF and MTTR that did not reach the target on the TSR machine. Furthermore, to identify the root cause of the problem, they use DMAIC tools (Define, Measure, Analyze, Improve, and Control) with supporting methods of Root Cause Analysis and Why Why Analysis as a reference for maintenance. The results of this study indicate that the MTBF and MTTR values have reached the target after the maintenance is done.

Another study conducted by Rahimdel et al. (2015), where the problem that occurs is the level of reliability of an electrical system on the Electrical-Hydraulic Rotary Drilling System machine. To overcome these problems, they use the implementation of Preventive Maintenance or repairs before future failures. This study indicates an increase in the reliability of the Electrical-Hydraulic Rotary Drilling System machine system after the Preventive Maintenance steps are carried out.

Based on a previous study in order to solve company's problem, we use the combination of Lomte et al. (2018) and Rahimdel et al. (2015) research, namely MTBF, MTTR, DMAIC method, and Preventive Maintenance.

1.1. Objectives

The purpose of this study is:

1. To determine the level of reliability of the Gas Engine.
2. To find out the root cause of the problem.
3. To propose and advise the company to implement preventive maintenance to prevent the occurrence of a breakdown that causes downtime in the Gas Engine.

2. Literature Review

2.1 Reliability

According to Heizer et al. (2020), reliability is the probability that the machine or product will function properly within the specified time based on the prevailing conditions. In general, reliability is defined as the ability of a functional unit to perform the required function under certain conditions for a certain time interval (Vaidya et al., 2020). According to Rahimdel et al. (2015), reliability is the probability that a tool used will function factually for a predetermined period. The basic unit of measure for reliability is the failure rate (FR). Perhaps the most common term in reliability analysis is the mean time between failures (MTBF), which is the inverse of FR(N) (Heizer et al., 2020).

2.2 Mean Time Between Failure (MTBF)

According to Heizer et al. (2020), MTBF is the average time between the first failure and subsequent failure of a component, machine, process, or product. According to Torrel and Avelar (2010), MTBF is the average time required by the system to work without experiencing failure within a certain period. Then, according to Lomte et al. (2018), MTBF is when the first breakdown should be at 8 a.m., and the second breakdown occurs at 8 a.m. According to Busse et al. (2015), MTBF is a measure to determine the average operating time between failures to calculate the user can calculate the machine's failure rate.

2.3 Mean Time To Repair (MTTR)

According to Heizer et al. (2020), MTTR is the average time for repairs carried out after a component, machine, process, or product failure. According to Lomte et al. (2018), MTTR is the expected time for repair after the first failure (Breakdown at 8 a.m.), so the processing time for repairs is more optimal. According to Uyun et al. (2018), MTTR is the average component repair time or downtime carried out over a certain period.

2.4 Define, Measure, Analyze, Improve, and Control (DMAIC)

According to Lomte et al. (2018), DMAIC can use several methods such as Pareto Chart, 5Why, and RCA to detect repetitive breakdown of each Define, Measure, Analyze, Improve, and Control (DMAIC) step. Mustapha and Habidin (2016) explained that the DMAIC approach is used to identify the causes of problems that affect the KTM Commuter Station machine service quality. Then, Rehman et al. (2018) explained that the DMAIC methodology is used to identify problems so that improvements can occur. According to Hakimi et al. (2018), the DMAIC methodology is used to improve the quality characteristics of the company's product under study (Yoghurt).

2.5 Preventive Maintenance

According to Heizer et al. (2020), preventive maintenance is carrying out routine inspections to build a system that will find potential failures and make changes or improvements that can prevent failures. Rahimdel et al. (2015) explain that preventive maintenance is a predetermined work carried out according to schedule to prevent wear or sudden failure of equipment components. Basri et al. (2017), the basic principle of a preventive maintenance system involves predetermined maintenance tasks that come from the function of the machine or equipment and the life of the component. Therefore, tasks are planned to change components before they fail and are scheduled during machine downtime or shutdown.

3. Methods

The method used in this research is Mixed Method with descriptive research type. According to Sekaran and Bougie (2016), mixed methods research aims to answer questions that cannot be answered by "qualitative" or "quantitative" approaches. Mixed method research focuses on collecting, analyzing, and mixing both data types, quantitative and qualitative, in one study. According to Saunders & Lewis and Thornhill (2016), the purpose of descriptive research is to get accurate data about an event, person, or situation. Descriptive research questions usually begin with, or include, 'Who,' 'What,' 'Where,' 'When,' or 'How.' Descriptive research usually involves collecting quantitative data such as satisfaction levels, production quantities, sales figures, or demographic data. Still, it can also require a collection of qualitative information, such as how a manager solves a problem. In this research, the researcher was doing descriptive research by analyzing performance through describing the breakdown data. Furthermore, the researcher also described the root cause and preventive action to anticipate this.

4. Data Collection

Data sources are obtained in the form of primary and secondary data. Techniques of collecting the data in the form of interviews and field observations. The study was conducted from October 2019 to March 2020. For the analysis of this study, the author first used calculations using the Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) methods using Gas Engine downtime data to measure the reliability level of Gas Engines. Then used Define, Measure, Analyze, Improve and Control (DMAIC) with supporting methods Root Cause Analysis and Why Analysis, which is processed based on interview data to identify the root causes of problems from the Gas Engine. Furthermore, based on the results of the DMAIC stage, it is used as a reference for the proposed application of Preventive Maintenance, which is processed based on interview data to minimize and prevent breakdowns that cause Downtime on Gas Engines in the future.

To answer the objectives of this research, the steps taken are:
1. Calculating the reliability value of each gas engine component using the MTBF & MTTR method.
2. Identify the root cause of the breakdown of the gas engine using the DMAIC method.
3. After doing the DMAIC stage, the authors propose that the company implement appropriate preventive maintenance to prevent engine failure.

4.1 Calculation of MTBF and MTTR

At this stage, what the authors do is look for the MTBF value with the following calculations (Lomte et al. 2018):

$$MTBF = \frac{\text{total available time} - \text{breakdown}}{\text{number of breakdowns}} \quad \text{in Hours} \qquad (1)$$

While MTTR can be calculated by the formula (Lomte et al. 2018):

$$MTTR = \frac{\text{total breakdown}}{\text{number of breakdowns}} \quad \text{in Hours} \qquad (2)$$

This research was collected Gas engine breakdown data from January 2018 to July 2019. This calculation was carried out to find the average time between failure (MTBF) and the average repair time after failure (MTTR). Furthermore, the MTBF and MTTR are compared with the MTBF and MTTR targets. The MTBF and MTTR targets are obtained according to the following calculations:

$$MTBF\ target = \text{total available time} - \text{breakdown tolerance} \quad \text{in Hours} \qquad (3)$$

number of breakdowns tolerance

Information:

Available Time/Target Operating Time of Gas Engine per month = 720 Hours
Downtime tolerance per month = 38 Hours
Breakdown frequency that must be done every month (tolerance) = 3 times

$$\text{MTTR target} = \frac{\text{total breakdown tolerance}}{\text{number of breakdowns tolerance}} \quad \text{in Hours} \qquad (4)$$

Information:

Downtime tolerance per month = 38 Hours
Breakdown frequency that must be done every month (tolerance) = 3 times

4.2. Identify the Root Cause of the Breakdown using the DMAIC Method

At this stage, the authors carried out the DMAIC stage (Lomte et al. 2018, Vaidya et al. 2020):

- **Define Phase:** at this stage, identify problems or breakdowns that occur by dividing the Gas Engine into two Zones, namely Zone 1 and Zone 2, based on the type of damage that occurs from each part.
- **Measure Phase:** at this stage, the Breakdown data that has been decomposed is separated based on the type of Gas Engine problem.
- **Analysis Phase:** at this stage, we will carry out RCA (Root Cause Analysis) with the Why-Why Analysis supporting method to find out the cause of the breakdown that repeatedly occurs in the Gas Engine.

Table 1. Why-why Analysis & Root Cause Analysis

WHY WHY ANALYSIS & ROOT CAUSE ANALYSIS		
Equipment Name:		
Problem:		
WHY	ROOT CAUSE	ACTION
Why 1:		
Why 2:		
Why 3:		
Why 4:		
Why 5:		

- **Improvement Phase:** at this stage, the performance improvement on the Gas Engine will occur if the inspection preparation is carried out properly. Using RCA and data analysis should be used to improve the process by designing creative solutions.
- **Control Phase:** The last phase of DMAIC is the control phase used to preserve the improvement results of the project. Industrial maintenance teams, in particular, should focus on monitoring machines, and process maintenance work must regularly follow Inspection and maintenance standards for continuous improvement and reliability of processes and machines.

4.3 Preventive Maintenance

After doing the DMAIC stage, the researcher proposes to the company to implement the right Preventive Maintenance to prevent machine failure.

5. Results and Discussion

5.1 Analysis of MTBF and MTTR

In the first stage, the author is looking for the MTBF and MTTR values to measure the reliability of the Gas Engine while at the same time comparing with the target value. The calculation results are as follows.

Table 2. Data on the Calculation of MTBF & MTTR UNIT 1 Period January 2018 – July 2019

Month	MTBF Target	MTBF	MTTR Target	MTTR
January 2018	227,33	117,6	12,66	26,4
February 2018	227,33	226,33	12,66	13,66
March 2018	227,33	168,5	12,66	11,5
April 2018	227,33	116	12,66	28
May 2018	227,33	118	12,66	26
June 2018	227,33	168,75	12,66	11,25
July 2018	227,33	165	12,66	15
Augustus 2018	227,33	169	12,66	11
September 2018	227,33	78,33	12,66	41,66
October 2018	227,33	153	12,66	27
November 2018	227,33	163,75	12,66	16,25
December 2018	227,33	96,67	12,66	23,33
January 2019	227,33	152,25	12,66	27,75
February 2019	227,33	164,25	12,66	15,75
March 2019	227,33	128,25	12,66	51,75
April 2019	227,33	168	12,66	12
May 2019	227,33	118,4	12,66	25,6
June 2019	227,33	135,8	12,66	13,66
July 2019	227,33	228	12,66	12

Source: The Company (2020)

Based on Table 2 above, the MTBF value that reached the target was 227.33, namely in July 2019 with an MTBF value of 228, and the MTTR value that reached the target of 12.66, namely in March 2018, June 2018, August 2018, April 2019, and July 2019 with MTTR values are 11.5, 11.25, 11, 12, and 12. Compared to previous research, Lomte (2018), within six months, it can achieve the target for four months for MTBF, while for MTTR, it does not achieve the target for one month.

Based on the table above, the number of MTBF and MTTR results that do not reach the target, this is used as a reference for the author to find the root causes and causes of not achieving the MTBF and MTTR targets using the DMAIC (Define, Measure, Analyze, Improve, Control) method supporters of Root Cause Analysis (RCA) and Why-why Analysis.

5.2 DMAIC Stage (Define, Measure, Analyze, Improve, Control)

- **Define Phase:** At this stage, identifying of problems or breakdowns occurs by dividing the Gas Engine into two Zone parts, namely Zone 1 and Zone 2, based on the type of damage from each part. Zone 1 – Engine System and Zone 2 – Radiator or Cooling System. The following is the frequency of damage that occurs repeatedly or Repetitive Breakdown on the Gas Engine after the division of Zones (Zone 1 and Zone 2).

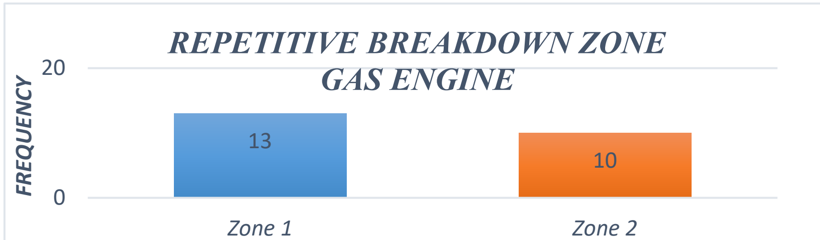

Figure 1. Repetitive Breakdown by Gas Engine Zone

The Gas Engine Zone is divided into two parts based on the picture above. Zone 1 is the Engine System, with a Breakdown frequency of 13 times, and Zone 2 is a Radiator / Cooling System with a Breakdown frequency of 10 times. It is used to get more detailed results in finding the root cause of each zone's problems (Zone 1 and Zone 2)

- **Measure Phase:** At this stage, measurement of problems or breakdowns that occur in each part will be carried out based on Zone (Zone 1 and Zone2) as described in Table 3 and Table 4 below:

Table 3. Repetitive Breakdown ZONE 1

Repetitive Breakdown Gas Engine			
ZONE 1 – ENGINE			
No.	Problem	Breakdown Frequency	Downtime (hours)
1	Sparkplug Failure	5	50
2	Thermal Couple Error	2	192
3	MRS (Metering Regulating) Damage	2	16
4	Overhaul Inspection	1	168
5	Motor Generator Failure	1	192
6	Timing PCV (Press Control Valve) not Balance	1	20
7	Gas Train Broken	1	8

Source: The results of processing the data (2020)

Table 4. Repetitive Breakdown ZONE 2

Repetitive Breakdown Gas Engine			
ZONE 2 – RADIATOR / Cooling System			
No.	Problem	Breakdown Frequency	Downtime (hours)
1	Radiator Failure	6	432
2	CAC (Charge Air Cooler) Failure	3	72
3	Intake Air Filter Failure	1	6

Source: The results of processing the data (2020)

Note:
- Problem: Damage of the type of Part on the Gas Engine
- Breakdown Frequency: Frequency of damage to each Gas Engine Part
- Downtime: The time the machine does not operate and repair caused by the breakdown that occurs.

After getting the Breakdown frequency with the Downtime time of each part, the Analysis stage is carried out using the Root Cause Analysis method with the Why-why Analysis method.

- **Analysis Phase:** At this stage will carry out an RCA (Root Cause Analysis) to support Why-why Analysis on the Repetitive Breakdown of Gas Engines after being divided into two Zones. The following is an example of a Why-why Analysis & Root Cause Analysis Zone 1 – Engine System – Sparkplug Failure table below:

Table 5. Why-why Analysis & Root Cause Analysis Zone 1 – Engine System – Sparkplug Failure

WHY WHY ANALYSIS & ROOT CAUSE ANALYSIS		
Equipment Name: Gas Engine – Zone 1 – Engine System		
Problem: Sparkplug Failure		
WHY	ROOT CAUSE	ACTION
Why 1: Scorched Spark Plug	Combustion emissions stick, and the carburetor or injection is not reset	Fixed Wiring & Replace Sparkplug
Why 2: The air supply in the combustion chamber is too large.		
Why 3: Unbalanced quantity of oxygen and fuel		
Why 4: Low compression		

Source: The results of processing the data (2020)

NOTE: Furthermore, using the tool Why-Why analysis, the root cause of the damage to the other Zone 1 and 2 can be identified.

In Table 6, the writers explain the root cause and action in zone 1 and 2:

Source: The results of processing the data (2020)

Table 6. Recapitulation of Root Cause Analysis and Action Zone 1 and 2

Zone	**Problem**	**Root Cause**	**Action**
1	Sparkplug Failure	Combustion emissions stick, and the carburetor or injection is not reset	Fixed Wiring & Replace Sparkplug
	Thermal Couple Error	Short circuit on Wiring	Reset Module, Change or Fixed Wire, Replace PCB (Printed Circuit Board)
	Metering Regulating System (MRS) Failure	Dust and dirt accumulate	Clearing gas filter, lubricating valve hinges, cleaning fuel injection, replacing MRS
	Overhaul Inspection	Oil mixed with iron flakes (dirt)	Replace Ring Piston, cleaning block Engine, Wiring, Engine Testing
	Motor Generator Failure	Friction between Flywheel and Crankshaft	Replace Motor, Gear Motor Lubrication.
	Press Control Valve (PCV)	The amount of dirt (dust) that blocks the flow of air in	Replace PCV (Press Control Valve), Air duct cleaning, replace air filter.
	Gas Train Failure	Fuel Setting is too low, Injection Fuel is dirty	Replace & Clean the Fueling System as a whole
2	Radiator Failure	Lack of lubrication and Error in installation	Clearing Radiator, Replacement on Marble Bearing
	Charge Air Cooler (CAC) Failure	The amount of scale in the pipeline	Replace CAC and Clean Engine Cylinder Block
	Air Intake Filter Failure	Incoming air is mixed with dust.	Air Intake Change, Air Intake Chamber Cleaning

- **Improvement Phase:** Machines will improve their performance if the proper checklist is prepared. Preventive cleaning and maintenance checklists help reduce machine breakdowns.
- **Control Phase:** In this stage, regular checks will be made to implement Preventive Maintenance, such as replacing damaged parts or steps to prevent damage from occurring.

5.3 Implementation of Preventive Maintenance

Based on the results of the DMAIC analysis above using the Root Cause Analysis and Why–why Analysis methods, then we conducted interviews with the company's Operational Manager for preventive actions or preventive Maintenance to reduce the occurrence of Breakdowns in Gas Engines in Zones 1 and 2 for the future. The result is as follows:

Table 7. Preventive Maintenance Zone 1 – Engine System

Problem	Root Cause	Preventive Action	Information
Sparkplug Failure	Combustion emissions stick, and the carburetor or injection is not reset	1. Cleaning 2. Injection Check	1. Briefing on workers 2. Periodic testing of components
Thermal Couple Error	Short circuit on Wiring	Adjustments on components	Periodic maintenance of components related to measuring instruments on Gas Engines
Metering Regulating System (MRS) Failure	Dust and dirt accumulate	Adjustments on components	Periodic maintenance of components related to measuring instruments on Gas Engines
Overhaul Inspection	Oil mixed with iron flakes (dirt)	1. Worker Training 2. Emphasis on SOP 3. Installation of Filter Components	1. Conducted training by expert technicians for cleaning and lubrication of Gas Engines 2.Maintenance Checklist is done in detail 3.Increase filtering on filter components
Motor Generator Failure	Friction between Flywheel and Crankshaft	1. Clearing Check 2. Periodic lubrication	1. Check the condition of the oil regularly 2. Regular cleaning of the oil filter
Press Control Valve (PCV)	The amount of dirt (dust) that blocks the flow of air in	cleaning regularly	Make a Clearing Checklist for cleaning the pipeline on the valve pipe
Gas Train Failure	Fuel Setting is too low, Injection Fuel is dirty	1. cleaning regularly 2. Emphasis on SOP	1. Creating a Clearing Checklist for cleaning 2. Controlling cleaning activities

Source: The results of processing the data (2020)

Table 8. Preventive Maintenance Zone 2 – Radiator / Cooling System

Problem	Root Cause	Preventive Action	Information
Radiator Failure	Lack of lubrication and Error in installation	1. Clearing Radiator 2. Checking the Radiator Water regularly 3. Worker training	1. Create a Clearing Checklist for radiator cleaning 2. Detailed recording on the Air Coolant radiator 3. Conducted training by skilled technicians
Charge Air Cooler (CAC) Failure	The amount of scale in the pipeline	Component replacement	Perform a replacement procedure on the filter according to the module from the manufacturer
Air Intake Filter Failure	Incoming air is mixed with dust.	cleaning regularly	Make a Clearing Checklist for cleaning the drainpipe on the Air Intake

Source: The results of processing the data (2020)

Based on Table 7 and Table 8 above, obtained the results in preventive measures or Preventive Action, namely Adjustment on components, Training for workers, Emphasis on SOPs, Clearing Checklists, changing components, and checking the Radiator fluid regularly correctly. It is done to minimize the damage that occurs to the Gas Engine. According to Lomte et al. (2018), to prevent failure first is by inspecting and repairing defects, and second is by applying countermeasure on failure parts. Continuous improvement and reliability are created by doing inspection & maintenance. Furthermore, to prevent failure, Rahimdel et al. (2016) used preventive maintenance scheduling for the electrical system before 1400 hours of operation and stopped the drilling fleet.

6. Conclusion

During 18 months from January 2018 to July 2019, the average MTBF target value was 227.33 hours, and the average MTTR target value was 12.66 hours. During this period, many MTBF and MTTR still have not reached the target. The root of the problem that causes Downtime on Gas Engines is caused by the breakdown of parts or components on Gas Engines. The identification results of the root cause indicate that the Gas Engine is damaged in two Zones. Namely, Zone 1 - Engine System, namely emissions from combustion sticking and the Carburetor or Injection is not reset, Dust and dirt accumulate, oil mixed with iron flakes (dirt), friction between the Fly Wheel and Crank Shaft, a lot of dirt (Dust) that obstructs the air inflow, the fuel setting is too low, and the fuel injection is dirty. Meanwhile, in Zone 2 – Radiator or Cooling System, there is a lack of lubrication and errors in installation, the amount of crust in the pipeline, and the incoming air is mixed with Dust. Preventive steps to minimize damage to the gas engine are component adjustments, worker training, emphasis on SOPs, clearing checklists, component changes, and regular checks on radiator fluid properly.

References

Akhir, D. J., Cara PLN Jadikan Indonesia Kekuatan 10 Besar Ekonomi Dunia, Juni 19, Available: https://economy.okezone.com/read/2019/03/22/320/2033774/cara-pln-jadikan-indonesia-kekuatan-10-besar-ekonomi-dunia?page=1, 2019.

Badan Koordinasi Penanaman Modal (BKPM). Daftar Investasi Asing di Triwulan II 2019*,* Juni 2019, Available: https://www.bkpm.go.id/id/statistik/investasi-langsung-luar-negeri-fdi, 2019.

Basri, E. I., Razak, I. H. A., Ab-Samat, H., & Kamaruddin, S. Preventive maintenance (PM) planning: a review. *Journal of Quality in Maintenance Engineering*, 2017.

Busse, S., Hiller, M., Kahlen, K., and Himmelmann, P., MTBF comparison of cutting edge medium voltage drive topologies for oil & gas applications, *In 2015 Petroleum and Chemical Industry Conference Europe (PCIC Europe),* pp. 1-13, 2015.

Kang, N., Zhao, C., Li, J., & Horst, J. A. A Hierarchical structure of key performance indicators for operation management and continuous improvement in production systems. *International journal of production research*, *54*(21), 6333-6350, 2016.

Lomte, R. U., Bhosle, S. P., Ambad, P. M., and Gaikwad, R. A., Reliability Improvement for TSR Machine of Banburry Mixer using Plant Optimization Process, *Procedia Manufacturing*, vol. 20, pp. 440-445, 2018.

Mustapha, R., and N. F. Habidin. "Using DMAIC improvement of customer satisfaction and facilities provided at commuter station (Malaysia)." *International journal of academic research in business and social science (6)* 2, no. 821-836, 2016.

Hakimi, S., Zahraee, S. and Mohd Rohani, J., Application of Six Sigma DMAIC methodology in plain yogurt production process, *International Journal of Lean Six Sigma*, vol. 9, no. 4, pp. 562-578, 2018.

Heizer, J., Render, B., & Munson, C., *Operations management: Sustainability and Supply Chain Management*, 13th Edition. Harlow: Pearson Education Limited, 2020.

Rahimdel, M. J., Ataei, M., & Khalokakaei, R. Reliability Analysis and Maintenance Scheduling of the Electrical System of Rotary Drilling Machines. In *Current Trends in Reliability, Availability, Maintainability and Safety* (pp. 623-632). Springer, Cham, 2016.

Rehman, S., Khan, S., Kusi-Sarpong, S. and Hassan, S., Supply chain performance measurement and improvement system: A MCDA-DMAIC methodology, *Journal of Modelling in Management,* Vol. 13 No. 3, pp. 522-549, 2018.

Saunders, M., Lewis, P., & Thornhill, A. *Research Methods for Business Students 7th Edition*. Harlow: Pearson Education. 2016.

Sekaran, U & Bougie, R. *Research Methods for Business*. Hoboken, New Jersey: John Wiley & Sons Ltd. 2016.

Torrel, W and Avelar, V., *Mean Time Between Failure: Explanation and Standards*, Washington: APC-Schneider, 2010.

Uyun, L. M., Sandora, R., & Setiani, V., Probabilitas Human Error dan Reliability pada Area Kerja Mesin Boiler. *In Seminar K3,* vol. 2, no. 1, pp. 455-462, 2018.

Vaidya, S., Bhosle, S., & Ambad, P., DMAIC Approach to Improve Carbon Weighing Compliance of Banbury Machine, *In Computing in Engineering and Technology,* pp. 803-816, 2020.

Xiang, Z. T., & Feng, C. J. Implementing total productive maintenance in a manufacturing small or medium-sized enterprise. *Journal of Industrial Engineering and Management*, *14*(2), 152-175, 2021.

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