Enhancing Overall Equipment Effectiveness through Total Productive Maintenance and Root Cause Analysis: A Case Study on Melka Wakena Hydroelectric Power Plant

Solomon Mekuria Embiale

A Thesis Submitted to the Department of Mechanical Engineering

College of Mechanical, Chemical, and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Manufacturing Engineering

School of Postgraduate Studies

Adama Science and Technology University

June, 2025

Adama, Ethiopia

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Thesis Supervisor:

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I hereby declare that this Master Thesis entitled **"Enhancing Overall Equipment Effectiveness through Total Productive Maintenance and Root Cause Analysis: A Case Study on Melka Wakena Hydroelectric Power Plant"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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With sincere gratitude,

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ABSTRACT

Overall equipment effectiveness is a critical performance evaluation standard used in industries with high asset-based operations to quantify the degree to which equipment is utilized. In hydroelectric power plants, Overall equipment effectiveness is vital, as availability, performance, and reliability of generation units have direct effects on generation of power, plant efficiency, and national energy production. The aim of this study is to enhance Overall equipment effectiveness at Melka Wakena Hydroelectric Power Plant by using Total Productive Maintenance and Root Cause Analysis. The study addressed major maintenance-related issues, including frequent machine breakdowns, and a lack of synergy between production and maintenance management. Through a comprehensive analysis involving observation of the production process, historical data collection, real-time monitoring, interviews with plant personnel and questionnaires for managers, maintenance personnel, and operators for data collection. The research evaluated the impact of Total Productive Maintenance and Root Cause Analysis on Overall equipment effectiveness by partial least square structural equation modeling (PLS-SEM), equipment downtime, performance efficiency, operational reliability, and safety standards. The study also identified the root cause of low Overall equipment effectiveness and frequent causes of machine failures through Root Cause Analysis tools, the Fishbone diagram along with the 5 whys technique and using the Pareto chart the major contributor to the problem was determined. From the study, the OEE of the power plant working units was found 55% which is the lowest value compared with the world-class 85 % OEE. The results proved that Total Productive Maintenance and Root Cause Analysis have a significant impact on the improvement of the Overall equipment effectiveness of the case power plant and the suggested solution provided for the identified problems through Root Cause Analysis. This research assessed the strategic importance of Total Productive Maintenance in improving the energy production and operational efficiency in the hydroelectric power plant.

Keywords: *Total productive maintenance, Overall equipment effectiveness, Root Cause Analysis, Partial Least Square Structural Equation Modeling.*

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ACRONYMS

AM	Autonomous Maintenance
CEO	Chief Executive Officer
EEP	Ethiopian Electric Power
HEPP	Hydroelectric Power Plant
OEE	Overall Equipment Effectiveness
PLS-SEM	Partial Least Square Structural Equation Modeling
PM	Preventive Maintenance
RCA	Root Cause Analysis
SOP	Standard Operating Procedure
TPM	Total Productive Maintenance
TQM	Total Quality Management

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The study was carried out at the Melka Wakena hydroelectric power station in the upper basin of the Wabe Shebelle River and utilizes the catchment area solely for power generation. The power plant is located at the high land bale zone admiration far from the equator (at $70° N$), and at the distance of about $280Km$ from Addis Ababa in the Southeast direction. The initial project design of the power station project was done by the French Company "Electricity de France Cooperative Program" on behalf of the Imperial Ethiopian Government. The power station project report on the Wabe Shebelle River is done by the "Hydro Project "Institute (USSR). The hydropower plant was commissioned in 1988. The head work consists of an earth and rock fill dam, with a total crest length of $1800m$ and a height of 38m. The dam creates a reservoir with a surface area of 8160 hectares of a $763\ x\ 106\ m^3$ storage capacity. The reservoir provides water withdrawal of up to $60m^3/sec$ to the open head race channel. The power station has a total installed capacity of $153\ MW$ from 4 Generating units rated at $38.25\ MW$ each at an operating head of $300\ meters$. The four units are housed inside Surface Powerhouse comprising of Vertical Francis Turbines. The Power is generated at a $13.8\ KV$ voltage level and then stepped up to $230\ KV$. There are four intake lines from the power generation plant to the switchyard and three output lines, Koka I, Koka II, and Shashemene (Yugoslav) lines, from the Melka Wakena hydroelectric power plant. In current global conditions where competition is increasing, enterprises need to increase their profitability to ensure their continuity in their activities or to include plans aimed at minimizing the total cost resulting from these activities. These plans have great importance in managing the operational activities that can be classified under the titles of production, personnel, material, and maintenance systematically and effectively (Özcan et al., 2020).

Especially to realize these objectives, the machinery, equipment, and devices at the production facilities must perform the intended operations on time, continuously, in high quality, and reliably. In this way, proper management of the other three principal processes (production, personnel, and material) is greatly facilitated by the planning of maintenance activities, and improving operational effectiveness is largely dependent on the organizational administration of maintenance planning activities (Gelaw et al., 2024).

Besides the contribution of the maintenance planning activities mentioned above, it is important to reduce all operating expenses because, depending on the nature of the operation, between 15 and 70 percent of overall production expenses are maintenance expenses. A most commonly utilized method states that maintenance expenses comprise labor, replacement parts, and service charges. If a breakdown or maintenance request results in a halt in the business, the losses for every duration that production cannot be attained should be charged as a cost and included in the management process (Gelaw et al., 2024).

1.1.1 Hydroelectric power plant

Hydroelectric power plants are a component of systems that generate, transmit, and distribute electricity. A substation's voltage changes from high to low and vice versa, or it can carry out many other crucial tasks. At a powerhouse, voltage is generated and changes from low to high. Electricity may pass via many substations at varying voltages between the generating units and consumers. A power system's substation is a crucial component that serves as a link between the distribution system, transmission systems, producing stations, and load points. Here, I'll discuss the main parts of the powerhouse to provide a broad overview of the assets of the power plant that are necessary for both power generation and the maintenance that is being done on them (Bezabih, 2021). These are;

1. Spherical valve

A spherical valve is the equipment by which water is pumped out of the penstock tube and into the turbine. It shall function if the penstock side pressure and turbine pressure are balanced out by the bay pass, and the spherical valves mounted on the penstock are specialty high-pressure shut-off valves. Shutdown in the course of normal shutdown or turbine trip operation is their primary function. They are valve bodies that are cast steel or steel welded. When a signal is passed from the start button of the control room or machine room to the spherical valve, the bay pass opens in such a manner that there is pressure equalization on the penstock side as well as on the turbine side. The spherical valve will be in readiness for opening if the side pressures are identical and the pressure sensor will perceive that the pressure difference is zero. Since the pressure on the turbine side is equal to the pressure on the penstock side, the seal on the penstock side gets relieved and released , after this, all condition is fulfilled the spherical valve freely opens.

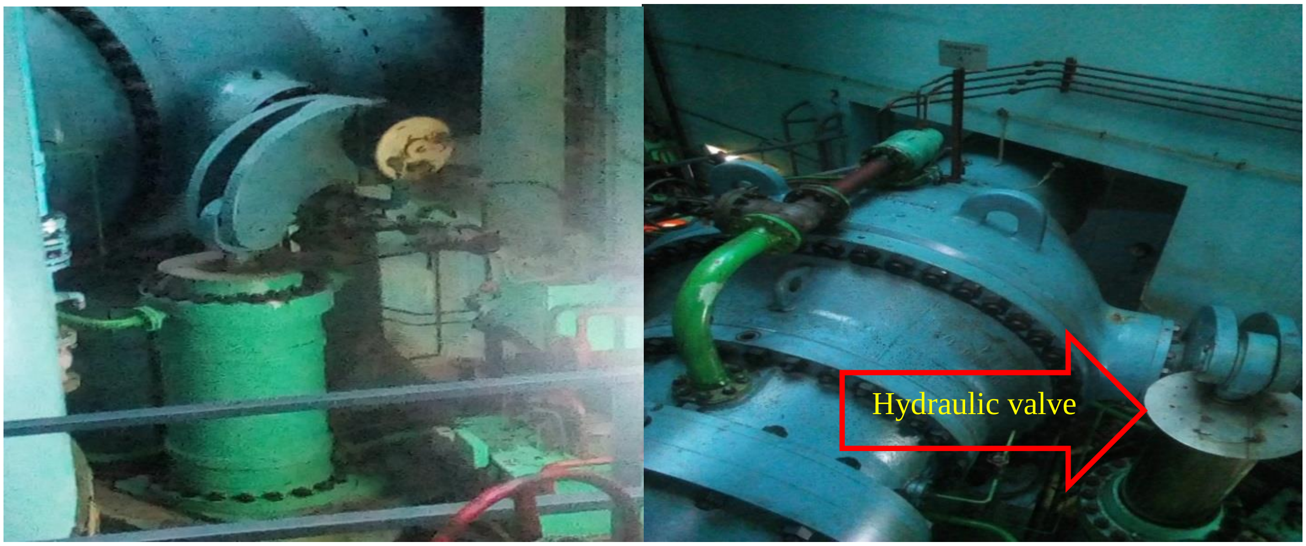

Figure 1.1 a) closed spherical valve and b) open spherical valve (under operation)

2. Governor system

A governor is a device that plays a vital role in the production of electric power by controlling the parameter that makes the machine under damage .governor system is a system or process in which a governor takes an action to protect a machine (units). There are two types of governor an electrical governor and a mechanical governor. The mechanical governor is commanded by the electrical governor and then the mechanical governor acts upon a command it receives from the electrical governor**.**

The governor is the one who controls the wicket gate to open or close by using either gas or oil to drive the wicket gate. The governor controls wickets gate by oil; when the load is added, the rotation speed of the turbine decreases, so the governor orders the wickets gate to open some percent of the wickets gate by pushing oil to open more to obtain its frequency constant. The frequency constant to be obtained for the runner should be rotated with 100% or 600 rpm. If the governor cannot control the wickets gate the system gets over speed. The over-speed damage (over speed occurs when the speed of the turbine reaches 150 % of the normal or 600 rpm, which means that speed is 900 rpm.) system unit, unless the vertical shaft of the fore bay is closed down completely. The system is safe when the vertical shaft closes the penstock; the speed of the turbine slows down, and lastly stops.

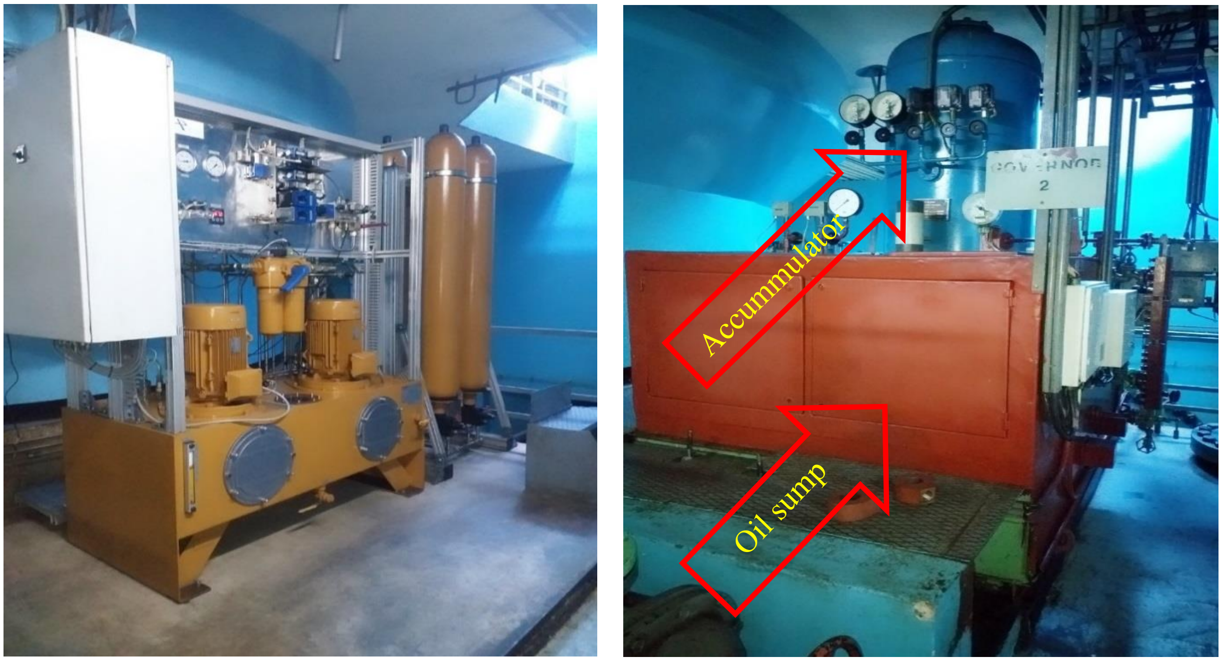

Figure 1.2 a) Governor work by gas, and b) governor work with oil

3. Turbine

The Melka Wakena hydro power plant uses one of the reaction turbines that are used for medium head known as the Francis turbine.

When the turbine is run or operates the temperature of the system is increased. Increasing the temperature is dangerous to the system. The temperature of the system is regulated by a water cooling system. The water used for the cooling system is coming from the tailrace by pumping. Therefore, the cooling system of the turbines is water.

Figure 1.3 Francis Turbine covered with its housing.

OEE is one of the key metrics that have a great impact on competitiveness in today's intense global competition as it is one of the Key performance indicators (KPI) in manufacturing. In hydroelectric power plants, availability, performance, and machine quality are crucial for production increase and meeting or pleasing the customer. Maintenance activities must be properly managed to enable a quality product at a low cost so that manufacturing companies will be in a position to compete in the global market. In an Ethiopian hydroelectric power plant, the OEE of the plant is dependent on the type of maintenance strategy used, and the availability, and performance of machinery working in the power plant. Concerning power generation, the capacity of the plant reduces over time due to different reasons. The annual production of such power plants highly depends on the firm energy of the specific power plant which is based on the available water used for the entire year, the plant capacity factor, and the category of the plant whether it is peak plant or base plant.

In the case of the Melka Wakena hydroelectric power plant as per the specification given by the company, its firm energy is $430GWH$. So, the plant's annual production plan is based on this reference. The plant is peak plant type based on the Ethiopian electric power generation which is expected to run all its available units on the peak load that is for specific times of the day and the remaining times of the day that it can run some of the units. The power plant had four working units initially but now it has three units working. Even though firm energy is the base for the annual production of power the reduction of power output of the working units will affect the annual production which will be investigated in this research. Following is the actual annual production of Melka Wakena Hydroelectric Power Plant.

Table1.1: Actual annual production of Melka Wakena Hydroelectric Power Plant

Year (E.C)	Annual production (GWH)	Firm Energy(430GWH)	
		Difference (GWH)	Loss (GWH)
2007	446.9	16.9	-
2008	260.061	169.39	169.39
2009	404.362	25.638	25.638
2010	385.553	44.447	44.447
2011	393.705	36.295	36.295
2012	479.58	49.58	-

2013	417.592	12.408	12.408
2014	417.5	12.50	12.50
2015	417.9	12.1	12.10
2016	595	165	-

Source: Melka Wakena Hydroelectric power plant annual production report

1.2 Statement of the Problem

Ethiopian manufacturing companies have low production performance and high maintenance cost due to frequent breakdown of machines also caused by power interruption resulting from sudden power failure.

Most significantly in the case of this hydroelectric power plant, there is a reduction of power output from the installed capacity of 153MW to 85MW out of four units, and now one of the units is not operational owing to catastrophic failure. In addition to these, the remaining two units are generating 30MW, and the other unit has 25MW capacity from the installing capacity of 38.25MW in each unit.

As per the preliminary investigation and interviews with employees of the organization in the Hydroelectric Power Plant the following problems were observed.

- Sudden breakdowns of working units and production interruptions a common problem. The top managers embrace the firefighting approach; the effort to forestall the sudden downfall is less.
- The level of collaboration between the production department and the maintenance department was less; the senior management accorded more importance to production functions as opposed to maintenance-related functions.
- Most of the machines in the power plant are aged, whereby the break down is typical and thus the companies that made them ditched the machines and are not selling spare parts to the market.
- Training and education of operators and maintenance technicians to operate and maintain the old and new machines is almost non-existent.

All the above problems cause unnecessary trips of the plant, unnecessary maintenance costs, and complaints from customers for slow power supply, which is the interruption of power caused by the sudden shutdown of the power plant.

Such nagging problems and accompanying costs can be reduced through the implementation of TPM, and RCA. As TPM is a maintenance strategy targeting zero breakdowns, zero defects, and zero accidents through the involvement of all employees, it will help the power plant to solve the stated maintenance-related problems.

1.3 Objectives of the Study

1.3.1 General objective

The general objective of the research is investigating the Root Causes of Power Plant maintenance failure through TPM to enhance the Overall Equipment Effectiveness of the Melka Wakena Hydroelectric Power Plant.

1.3.2 Specific objectives

The specific objectives of this research are:

- To assess the status of the power plant generators' effectiveness through OEE.
- To assess the current maintenance practices through world best practice indices, especially with TPM metrics.
- To identify the root cause of failures and inefficiency of the power plant using RCA tools.
- To recommend appropriate solutions to improve OEE by reducing maintenance-related costs.

1.4 Significance of the Study

This study proposes to enhance the overall equipment effectiveness through total productive maintenance, which can significantly improve the power plant generators' power output, which can in turn increase the income of Ethiopian Electric Power (EEP), which governs the case power plant, and also this improvement of power output will reduce power fluctuation by regulating the power grid system. So, the study determines the major cause of the inefficiency of the power plant, which can help other Ethiopian Electric Power plants take the initiative for such kinds of research.

1.5 Expected Outcome of the Study

After the end of this research, the study will provide

- Overall Equipment Effectiveness (OEE), performance efficiency of equipment, operational reliability, and safety of the working area in the power plant improvement method will developed.
- Solutions to the problems will be developed that cause equipment downtime, many failures, and quality issues in the power plant.
- Enhancement techniques for the performance efficiency of equipment in the power plant will be developed.
- Enhanced employee involvement and awareness of training effectiveness in the power plant by recommending its relevance.
- Reduced failures since their root causes will be addressed through RCA techniques.

1.6 Scope of the Study

Based on the problem acquired in the Melka Wakena hydroelectric power plant which is the reduction of power output from the installing capacity of the power plant and the problem on maintenance strategy of the plant this research will go through the improvement of OEE by TPM concerning the TPM and RCA. The OEE of the hydroelectric power plant machinery will be determined. The study area is in Ethiopian Electric Power Generation, Melka Wakena Hydroelectric Power Plant.

- Data gathering from previous background on equipment performance, downtime circumstances, maintenance records, and quality issues related to plant equipment and the annual total production history of the plant.
- Monitoring tools applications (OEE) and systems to trace real-time data on OEE components using data collection from machine production reports, OEE calculation, and trend analysis.
- Data analysis to identify modes and root causes analysis of loss in efficiency with Pareto chart and fishbone diagram alongside with 5 whys techinque.
- The data collected by the questionnaire will be analyzed by PLS-SEM software to see the impact of TPM, and RCA on OEE.
- Recommending the appropriate solutions to the acquired problem from the result of root causes analysis and the analysis of TPM.

1.7. Motivation of the study

The main motivation for undertaking this study is to enhance the Overall Equipment Effectiveness (OEE) of the Melka Wakena Hydroelectric Power Plant through Productive Maintenance (TPM) and Root Cause Analysis (RCA). The most interest is to find the root cause of power plant inefficiency and failure offering the best solutions that will reduce maintenance cost and enhance work efficiency.

This study is highly significant as it seeks to reduce power generation loss from the plant-installed capacity, which equates to Ethiopian Electric Power (EEP) revenue. Through the improvement of equipment performance and reliability, the study seeks to reduce power variability and ensure the stability of the Ethiopian power grid system. Aside from this, the findings can also serve as a benchmark for the rest of the power plants under the Ethiopian Electric Power network to undertake similar research work towards maximizing maintenance strategies and working efficiency. In general, the trigger is a broader goal of helping towards the efficiency and sustainability of energy production in Ethiopia, and this is of maximum importance for Ethiopian economic development and energy security.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Equipment performance and reliability in industry are prime drivers of operational effectiveness, particularly for industries that are asset-intensive like power generation. OEE has emerged as a comprehensive and widely accepted metric for measuring manufacturing and utility system productivity. Three key elements, Availability, Performance, and Quality are captured by OEE, which makes it a powerful tool for identifying and eradicating inefficiency in equipment use (Acharya et al., n.d.).

In order to increase OEE, organizations increasingly adopted systematic maintenance approaches such as Total Productive Maintenance (TPM) and analytical techniques such as Root Cause Analysis (RCA). TPM promotes preventive maintenance practices through systematic and participation from all levels of the workforce, whereas RCA focuses on establishing the root causes of recurring failures. Together, these approaches contribute significantly towards reducing unplanned downtime, extended equipment life, and stable process performance (Rathi et al., 2023).

While application of OEE, TPM, and RCA has been extensively studied among manufacturing sectors, little research has been done on their combined application to hydroelectric power plants, particularly in the context of Ethiopia. As hydropower holds a central position in the Ethiopian energy mix, research into these practices has both practical and academic significance. The aim of this literature review is to critically evaluate existing research on OEE, TPM, and RCA, identify prevalent gaps, and establish the theoretical and empirical foundation upon which this study is built (Bezabih, 2021).

2.2 Equipment Maintenance

Equipment maintenance is the act of keeping a state or condition or the state of being in good condition. Almost all industries have a physical asset maintenance program. The reasons for maintenance activities are to give equipment operating capability, detect faults, and/or prevent functional failure. Industrial, commercial, and residential environment maintenance entails functioning checks, servicing, repairing or replacing necessary devices, apparatus, machines, building structures, and auxiliary utilities (Gelaw et al., 2024) The practice of equipment maintenance has been raised through time to include a comprehensive list of terms which represent various cost-saving actions for the use of equipment; these procedures can be performed before or after breakdown (Gelaw et al., 2024).

Maintenance is the integration of all technical and administrative actions that can be done, such as planning, monitoring, controlling, and supervising, in an effort to maintain a machine, system, or product in its original operating condition so that it can function continuously as specified (Erbiyik, 200 C.E.).

Additionally, maintenance entails corrective and preventative measures to maintain acceptable production conditions or the plant's operational system in the intended state. Maintaining system robustness and dependability at the lowest possible cost is the goal of optimal maintenance practices. The complexity of the machines, the rising requirement for robustness, and the rising costs of systems, materials, and labor all contribute to the growing significance of maintenance strategies as industry advances. Lack of appropriate maintenance rules or their non-implementation is one of the primary causes of inefficiencies and irregularities in production systems. Nonetheless, in recent years, the industrial, engineering, and academic sectors within operational management have recognized the significance of maintenance strategies, and appropriate attention has been (Erbiyik, 200 C.E.).

2.3 Total Productive Maintenance (TPM)

TPM is a holistic Japanese approach that endeavors to optimize equipment's overall effectiveness using total employee commitment, including top management and equipment operators (Bataineh et al., 2019). TPM is a maintenance commitment that extends beyond preventive and predictive maintenance (Prabowo et al., 2018). The activity of performing regularly scheduled maintenance operations to help prevent future unexpected breakdowns is called preventive maintenance. In short, it's repairing things before they break (Lemma et al., 2013). By continuously evaluating the health of the equipment in real-time, predictive maintenance expands on condition-based monitoring to maximize equipment performance and lifespan (Lozada-Cepeda et al., 2021).

There are several similarities between Total Quality Management (TQM) and TPM. Total quality management (TQM) is defined as a management strategy that focuses on customer satisfaction to achieve long-term success. Every employee in a (Nadiyah & Dewi, 2022). All staff works towards fulfilling the needs of the customer who is the next level in the system. Translating this from TPM, it means providing maximum support and service to all equipment users in a bid to discourage malfunctions and breakdowns from taking place. According to TPM, this means providing all equipment users with the best possible support and service to stop malfunctions and breakdowns before they start. The company takes part in a TQM endeavor to enhance procedures, goods, services, and workplace culture (Gelaw et al., 2024). The TPM concept provides a quantifiable OEE component for evaluating the equipment productivity of the manufacturing line. Companies must reorganize and enhance their competitiveness to meet this market need. To achieve this, organizations must reduce all waste generated from production (Sutoni et al., 2019). Several studies have examined the issues associated with the injection molding process in a company that manufactures vehicle components. The involvement of the entire organizational structure, from the Chief Executive Officer (CEO) to all employees, who must remain committed to the specified goals and their assigned responsibilities, is essential for the success of Total Productive Maintenance (TPM) (Ali, n.d.). The TPM maximizes utilization and productivity of equipment and fosters a motivating climate to encourage employee participation and excel over the competition in innovativeness, cost, reliability, and quality (Taisir & Almeanazel, 2010).

Operation staff members are tasked with maintaining the equipment with which they interact on a daily basis. The operations have been well planned and organized since inception. The highlight of TPM came in the form of "Autonomous Maintenance (AM)" (Kalpande, 2014). Preventive maintenance and AM are practiced in this method. Cleaning, checking, replacement of the components, and scheduled repairs are carried out for avoiding the downtime of production and sustaining the life of the machine so that it can run more smoothly (Taisir & Almeanazel, 2010).

TPM is also defined as strategy-based care teams for the optimization of equipment effectiveness by designing production systems' overall maintenance throughout the entire lifecycle of the equipment, including all the fields associated with equipment (planning, use, and maintenance) and covering every member of the organization (Herdiwan & Widiyanesti, 2015). OEE is a proven approach and a highly useful instrument that can be applied in production unit comparisons between various industries and diagnostics. If the corrective measures are structural and simple, the OEE can support long-planned or short-reaction actions (Lameijer et al., 2021).

TPM is essentially a newer maintenance approach created to garner the evolving maintenance requirements. TPM is an American practice of detailed maintenance that was perfected and created to work in the Japanese industrial context. It is now accepted in Japanese business and other Western nations as well (Acharya et al., n.d.). Total productive manufacturing, or alternatively known as ordered equipment-centered continuous improvement nonstop improvement, aims at realizing production efficiency by the identification, and elimination of equipment losses and momentum losses in the course of the production system's life cycle and by mobilizing the constructive participation of team-oriented workers at all stages of the control operating network (Sharma et al., 2007). Numerous literature studies illustrate that TPM programs can bring significant benefits to organizations if well executed (Gupta et al., 2015). In their research, TPM reduced the production cost and improved OEE, resulting in a triple profit growth in three years and a double growth in revenue from sales. The high rate of defect led the company to incur a high cost in product loss and quality of defective products (Guariente et al., 2017).

TPM allowed four failure root causes to be determined: human error, bad raw materials, inefficient machines, and work processes. Ranking the engine damage to the machines also allowed them to collect data and analyze it with the help of descriptive statistics and Pareto charts. Fewer machine failures and errors followed, which therefore caused fewer glove defects. There were fewer breakdowns of equipment and errors, which in turn meant there were fewer defects in the gloves. They demonstrated that TPM is all correlated significantly and positively with low-cost, high-quality performance and good delivery performance measures (Gupta et al., 2015). In his opinion, OEE is a good way of identifying and eliminating losses, thereby achieving an efficient production system for world-class manufacturing. Enhance its business performance in order to meet customers' constantly rising expectations. TPM is one such methodology that has immense potential in increasing productivity, and quality and reducing product cost (Corrales et al., 2020). OEE value can be enhanced by minimizing the breakdowns and changeover losses which are associated with availability and by minimizing the defects and setup scraps losses which are associated with quality (Guszahari et al., 2024).

TPM predominantly embraces manufacturing organizations as the best maintenance approach to enhance maintenance performance. Literature in the past indicated that TPM had a direct influence on production equipment performance improvement (Sutoni et al., 2019).

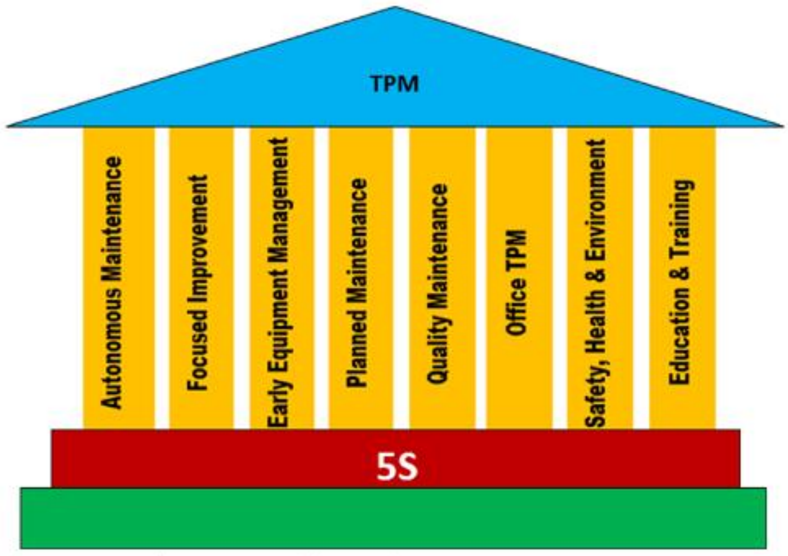

Figure 2.1 TPM Pillars (Gelaw et al., 2024)

2.4 Overall Equipment Effectiveness (OEE)

OEE is a method that measures the overall effectiveness of machines that can log the state of the manufacturing process to the level of product quality (Adesta et al., 2018).

Equipment performance and reliability have become critical concerns as companies re-engineer, downsize, and aggressively seek "lean" principles. Equipment performance measurement and improvement are nowadays a widespread issue in manufacturing factories. Overall equipment effectiveness (OEE) is the primary measure of PDCA (Plan-Do-Check-Act) continuous improvement cycle, particularly in production and maintenance systems. OEE enables organizations to monitor equipment performance (Check), gap out (Act), take corrective action (Do), and analyze results (Plan) to enable continuous operation improvement (Ogubuike Kingsley & E, n.d.).

OEE is a way through which monitoring and improvement of the efficiency of a manufacturing process is possible. It was initially introduced in 1988 by Nakajima as a Total Productive Maintenance key performance indicator (Corrales et al., 2020). Since the concept was created, OEE has been and remains a popular management tool used to measure and evaluate plant floor productivity. OEE is the productivity ratio of real manufacturing to what would be ideally produced. The majority of companies use OEE as a key tool, for example, in the implementation of lean manufacturing philosophies, or in the setup of maintenance programs and the monitoring of actual equipment performance (Corrales et al., 2020) Listed the metrics which measure OEE as availability, performance, and quality.

OEE takes the following factors into consideration; availability, performance, and quality can be calculated as expressed in the equation below developed by

$$OEE = Availability \times Performance \times Quality \times 100$$

The industry baseline OEE performance can be used for the comparison of current OEE values of manufacturing systems for the need to improve; this being one of the quantitative performance metrics. 85% OEE was given as an ideal rate that is also called a world-class rate for the calculation of the elements based on 90% availability rate, 95% performance rate, and 99% quality rate (Corrales et al., 2020); Some other research showed that OEE greater than 50% is acceptable based on real performance rate, quality rate, and availability of equipment. Typical production problems affecting OEE include breakdown (i.e., equipment failure), setup and adjustment, idling and minor stoppages, speed reduction, quality defects, and rework (Rathi et al., 2023).

ATS International B.V (2010) also implied that some of the benefits that can be achieved by a business organization in terms of adoption of a good system of OEE monitoring are reduced downtime, decreased repair costs, optimized labor efficiencies, improved quality, optimized personnel productivity, and improved production capacity.

2.5 Six Big Losses

From the large targets of TPM and OEE efforts is the elimination or the reduction what has come to be known as the Six Big Losses (Taisir & Almeanazel, 2010).

1. Equipment Failure

Equipment failure is any measurable amount of time when equipment should be being manufactured but is not running due to some type of failure. Another definition of equipment failure in broad terms is as any unplanned downtime or shutdown. Equipment Failure is an Availability Loss (ALMashaqbeh & Hernandez, 2024).

2. Setup and Adjustments

Setup and adjustments loss is any delay longer than usual where the equipment is intended to be produced but isn't running due to a changeover or another equipment adjustment.

Setups & Adjustments is a more general term to refer to any planned downtime. They are an Availability Loss (Nusraningrum & Senjaya, 2019).

3. Idling and Minor Stops

Idling and minor stop loss is the duration that the machinery idle for a short while (normally a minute or less) with stop released by the operator. Idling and Minor Stops also described by the name Small stops. Idling and Minor Stops is a Performance Loss (Satpatmantya et al., 2023) .

4. Reduced Speed

Reduced Speed is a time during which the equipment runs slower than the Ideal Cycle Time. Slow cycles are an alternative name for reduced speed. Reduced speed is a Performance Loss (Satpatmantya et al., 2023).

5. Process Defects

Process defects are faulty parts that are produced when there is constant-state production. They are the pieces scrapped and pieces re-workable due to the fact that OEE is showing quality in terms of First Pass Yield. Process defects are a Quality Loss (Martomo & Laksono, 2018).

6. Reduced Yield

Decreased yield is utilized to account for the defective parts produced from start-up to steady-state production to account for scrapped parts and re-workable parts, as OEE accounts for quality from a First Pass Yield perspective. Lower yield can be linked to any piece of equipment start-up, but is most commonly measured after changeovers. Lower yield is a quality loss (Martomo & Laksono, 2018).

Using the Six Big Losses format gives a concrete road map towards maximizing the OEE score (ALMashaqbeh & Hernandez, 2024).

- Cutting Availability Loss in the form of Equipment Failures or Setups and Adjustments guards against excessive unplanned stops or downtime, and reducing planned stops.
- Cutting Performance Loss due to Idling, Minor Stops, and Reduced Speed prevents minor stops and slow cycles from building up.
- Finally, minimizing Quality loss as Process Defects and Lower Yield decreases the number of unusable parts being manufactured before and during steady-state production**.**

2.6 Root Cause Analysis (RCA)

Root Cause Analysis or RCA is an organized, scientific method for the identification of a problem's root or underlying cause in place of trying to mend only its symptoms. Its main purpose is to find out why something did happen and make it impossible to occur again by setting subsequent corrective action. RCA is based on the fact that issues always have root causes and attempting to solve visible symptoms only would not provide a permanent solution (Nusraningrum & Senjaya, 2019). The process will typically involve distinctly identifying the issue, collecting relevant data, identifying possible cause factors, making up one's mind on the root causes by employing methods like the 5 Whys, Fishbone Diagram, Pareto Analysis, FMEA, or Fault Tree Analysis, and subsequently preparing and implementing corrective actions. Techniques like the 5 Whys encourage asking "why" repeatedly until the root cause is revealed, while Fishbone Diagrams visually categorize causes in areas like Man, Machine, Method, Material, Measurement, and Environment. Correct identification of the root cause leads to long-term improvements, prevents problem recurrence, enhances safety and quality, saves time and money, and instills a culture of continuous improvement (Danguche & Taifa, 2023). RCA is vital for organizations that want to achieve long-term success by addressing problems at the root so that they do not keep on resurfacing repeatedly (Amrani et al., 2022). The Fishbone Diagram or Ishikawa diagram is used in finding the probable cause of a problem. FMEA, on the other hand, is a pre-emptive approach where one identifies probable modes of failure and how severe they are. Root cause analysis is a basic process in helping organizations learn from mistakes and improve process quality. The root cause analysis will help in the prevention of similar mistakes being committed, improve efficiency, and increase productivity (Amrani et al., 2022). By identifying the root cause(s) of a problem, organizations can make informed decisions on how to mitigate and prevent the problem from reoccurring.

2.6.1 Fishbone diagram

A fishbone diagram is a graphical tool to enumerate the potential causes of a problem or a defect, also referred to as an Ishikawa diagram or cause-and-effect diagram. In maintenance management, the fishbone diagram is employed in Root Cause Analysis (RCA) to back-track equipment breakdowns, downtime, and inefficiencies to broader organizational and technical categories. These are usually Man (staff skills and training), Machine (equipment condition), Method (maintenance procedures), Material (quality of spares), Measurement (measuring equipment and KPIs), and Environment (work conditions). These main categories are also broken down into more specific sub-causes directly associated with maintenance shortcomings (Nusraningrum & Senjaya, 2019).

Diagram creation was achieved through joint brainstorming among operators, engineers, and maintenance staff to consider practical and technical causes. This was in line with the principles of Total Productive Maintenance (TPM), which emphasizes problem-solving in a systematic manner and operator participation. By identifying and eliminating the root causes such as inadequate preventive maintenance, inadequate training, or delayed availability of spare parts the fishbone diagram becomes a powerful tool in order to initiate corrective actions improving the OEE through enhanced maintenance strategies. The main categories of potential causes are typically indicated on the branches of the diagram. Each of these broad categories can then be further divided to narrow down to more specific potential causes. Construction of a fishbone diagram typically involves brainstorming potential causes with a group of stakeholders to ensure all potential causes are included (Holifahtus Sakdiyah et al., 2022).

2.6.2 Pareto chart

Pareto chart is a line graph of data that indicates relative weights of different categories or factors. It was named after Italian economist Vilfredo Pareto, who discovered that 20% of the Italian population held 80% of the country's wealth. A Pareto chart plots categories in descending order of weight, with the largest category on the left and the smallest category on the right. The graph also contains a cumulative percentage line that is the cumulative percentage of the total for which each group is accountable. A Pareto chart is commonly employed in process improvement and quality management to identify the causes most responsible for defects or problems. By focusing efforts on the limited range of categories covering the issues, organizations can use their resources to the best effect and achieve the greatest impact (ALMashaqbeh & Hernandez, 2024).

A Pareto chart is a quality control tool used to determine the most critical problems that are responsible for the quality of a product or service. Pareto principle or the 80/20 rule states that 80% of the problems occur because of 20% of the causes. Identifying equipment failure is one of the specific applications of the Pareto chart. To do this, data are gathered on the entire piece of equipment breakdowns that happen over some finite period and the reason behind those breakdowns are categorized. The categories may be things such as design error, improper maintenance, driver error, or external factors. Once groups have been defined, groups are ranked in order of frequency or severity, and a Pareto chart is constructed. The graph allows the analysts to see at a glance which kinds of equipment failures are causing most of the failures and direct efforts towards fixing those. Repairing the top several categories of equipment failure can assist in reducing downtime, increasing productivity, and improving safety (Amrani et al., 2022).

2.7 Multivariate Analysis and Structural Equation Modeling

Multivariate analysis is where statistical techniques that consider more than one variable at a time are employed. Researchers mostly apply first-generation statistical methods techniques such as multiple regression, logistics regression, and analysis of variance for analyzing data collected by numerous methods(Goodhue et al., 2006). The second-generation approach is currently utilized to analyze structural relationships known as structural equation modeling (SEM) which forces researchers to model the multiple and interrelated dependence within a single analysis. SEM's capability in testing multiple variables and levels of constructs, as well as complex measurement models, has enabled researchers to test complex relationships that could not be easily determined previously (Adeel et al., 2024). There are two forms of SEM: covariance-based SEM (CB-SEM) and partial least squares SEM (PLS-SEM). CB-SEM is used for theory testing and falsification, by determining whether a model is able to estimate the covariance matrix. PLS-SEM is used for theory development with emphasis on variance explanation in dependent variables, estimating path coefficients, and R2 values maximization of the target construct, for the prediction aims (Basbeth, F., & Ibrahim, 2018).

2.7.1 Reasons to use PLS-SEM

While using PLS-SEM there are three things to consider using the application of PLS-SEM which are:

- Research objective,
- Data characteristics
- Model complexity and evaluation

1. Research objective

PLS-SEM is a variance-based SEM approach, it uses ordinary least squares (OLS) regression with the goal of estimating coefficients that maximize the R2 values of the endogenous construct, therefore PLS-SEM best suited method for a predictive-oriented research objective, explanation of variance, and theory development. It provides R^2 values and indicates the significance of relationships among constructs (Basbeth, F., & Ibrahim, 2018).

2. Data Characteristics

A minimum sample size will guarantee that the outcome of statistical techniques possesses sufficient statistical power and that the findings of the statistical techniques are solid.

PLS-SEM is capable of dealing with small sample sizes since it is founded on the nature of ordinary least squares (OLS). PLS-SEM can deal with all measures scales: nominal, ordinal, interval, ratio scale, and binary coded data under constraints. PLS-SEM does not require normality of the data, since it is a nonparametric statistic. The advantage of PLS-SEM therefore can deal with highly non-normal data (e.g., extreme degree of skewness). Most missing data methods (e.g. pairwise deletion, mean replacement) can be used with fewer than 5% missing for any indicator (Basbeth, F., & Ibrahim, 2018).

3. Model complexity and evaluation

PLS-SEM handles many structural models or complex models and easily incorporates reflective and formative measurement models. Mediating and moderating effect analyses.

Table 2.1: Recommended sample size (80% of statistical power) (Basbeth, F., & Ibrahim, 2018)

Maximum Number of Arrows Pointing at a Construct	*Significance Level*											
	1%				*5%*				*10%*			
	Minimum R^2				*Minimum R^2*				*Minimum R^2*			
	0.10	*0.25*	*0.50*	*0.75*	*0.10*	*0.25*	*0.50*	*0.75*	*0.10*	*0.25*	*0.50*	*0.75*
2	158	75	47	38	110	52	33	26	88	41	26	21
3	176	84	53	42	124	59	38	30	100	48	30	25
4	191	91	58	46	137	65	42	33	111	53	34	27
5	205	98	62	50	147	70	45	36	120	58	37	30
6	217	103	66	53	157	75	48	39	128	62	40	32
7	228	109	69	56	166	80	51	41	136	66	42	35
8	238	114	73	59	174	84	54	44	143	69	45	37
9	247	119	76	62	181	88	57	46	150	73	47	39
10	256	123	79	64	189	91	59	48	156	76	49	41

2.7.2 PLS- SEM Model

To start a project we need to prepare the path model that shows the relationship among variables and hypotheses to be tested. In PLS-SEM construct is utilized to define a variable that is not measured directly by indicators, and hence also referred to as a latent variable. A PLS Path model is based on two theories: 1) Structural theory establishes how the constructs relate to one another in the structural model. The sequence and position of the constructs are theoretically determined by the researcher. The left variables are indicated as predicting the variables on the right. Latent variables used solely as independent variables are known as exogenous latent variables (Basbeth, F., & Ibrahim, 2018), whereas such latent variables that have only an acting role as dependent variables are termed endogenous latent variables.2) Measurement theory specifies the relationship between the constructs and indicators. The construct is represented as an oval or a circle. Relationships between constructs are shown by arrows. Single-headed arrows are taken as predictive relationships. Indicators are measured variables straightaway and depicted in the model as rectangles (x_1 to x_3) (Basbeth, F., & Ibrahim, 2018).

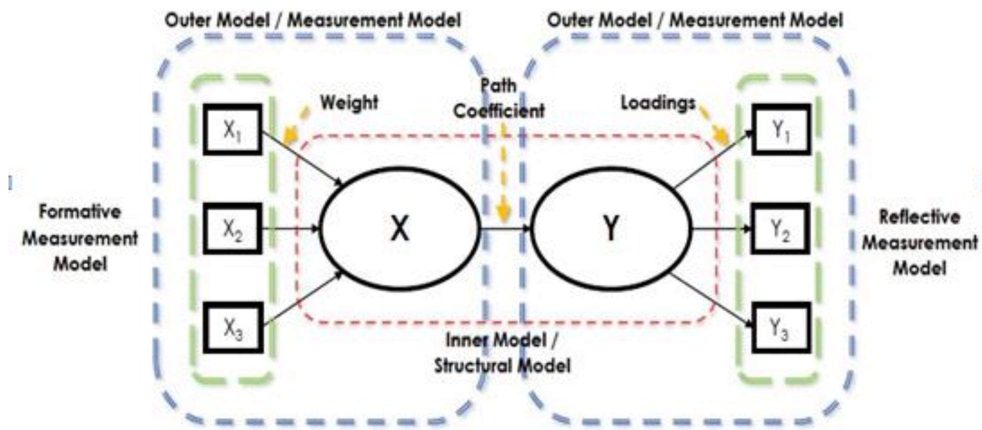

Figure 2.2 Example of path model

In a reflective measurement model, indicators have to be highly correlated with each other and interchangeable. However, construct X in Figure 2.3 is a formative measurement, where the assumption is that the construct is a product of causal indicators that are non-interchangeable and may be fully independent. Formative measures ought not to correlate. The arrows symbolize the causality going from the indicators towards the constructs (Basbeth, F., & Ibrahim, 2018).

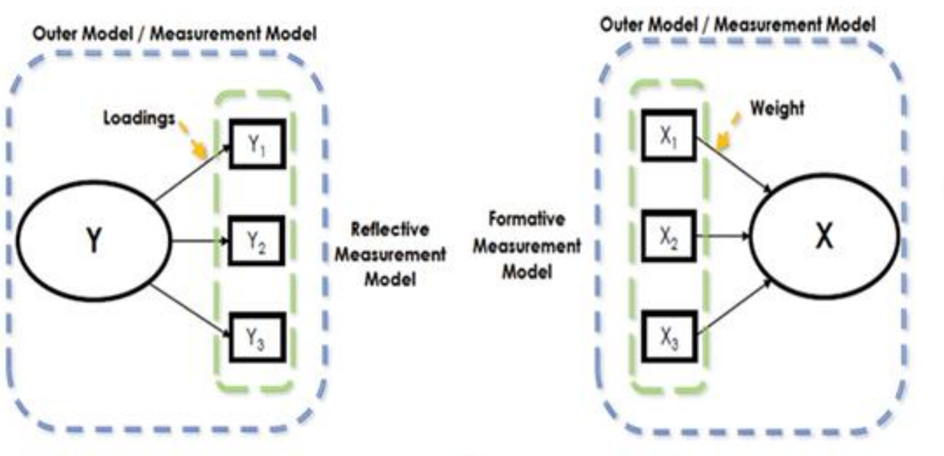

Figure 2.3 Reflective and Formative Measurement Model

2.8 Related works

2.8.1 Maintenance Practices in Hydroelectric Power Plants

(ÖZCAN et al., 2021) introduced the optimization of maintenance policies in hydroelectric power plants which successfully implemented the hybrid model that selects an optimal maintenance strategy. They integrated Multi-Criteria Decision Making (MCDM) methods, typically using the Analytical hierarchy process (AHP), Technique for order preference by similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for Enrichment evaluation(PROMETHEE) by the implementation of a hybrid model they showed that 100% reduction in unit shut down over a one year observation period. The selected maintenance strategy led to no malfunction of the main power transformer which resulted in the effectiveness of their proposed method in real-world applications. They contributed to bridging the gap in existing literature related to maintenance strategy selection specifically for hydroelectric power plants, which is the area that has seen limited study despite its relevance to global energy production.

(Musthopa et al., 2023) developed a maintenance model for the electric power distribution system by integrating three methodologies: Total Productive Maintenance (TPM), Reliability Centered Maintenance (RCM), and the four-discipline execution (4DX) method. They successfully proved that the implementation of the TRDX method led to a 50 reduction in feeder disturbances. Major improvement had been gained in various metrics, the system average interruption duration index (SAIDI) decreased by 29%, the system average interruption frequency index (SAIFI) decreased by 33%, energy not supplied (ENS) decreased by 32%, and the overall equipment effectiveness (OEE) the plant increased by 27%. Based on their finding they revealed that the TRDX method can enhance operational efficiency and reliability for industrial customers. They also clearly put the limitation of their study in that the findings are specific to one company and a short study period.

(Sharma et al., 2007) introduced the maintenance plan for turbine recovery machinery, in which they developed a Total Productive Maintenance plan for a vertical CNC lathe used in hydroelectric turbine recovery. They used the 5s methodology, sorting, setting in order, cleaning, standardizing, and sustaining workspaces around the lathe. They applied autonomous maintenance in which operators were trained to do daily checks like lubrication, cleaning, and minor inspection, planned maintenance activities were based on failure modes and effects analysis (FMEA) for identifying critical components, Safety, health, and environment (SHE) measure improved using personal protective equipment standardized signage and stricter environmental controls and they used maintenance management software to schedule and track preventive and corrective tasks. After the implementation of TPM, they obtained 79.9% availability, 95% performance, and 100% quality which resulted in 75.9%

OEE which is improved by nearly 30% that indicate an improvement in overall machine effectiveness. They got reduced downtime and better reliability of the vertical lathe. From FMEA analysis the authors identified 77 out of 192 components (40.1%) of the lathe were at high risk.

2.8.2 Total Productive Maintenance Implementation Methods

(Martomo & Laksono, 2018) introduced the analysis of Total Productive Maintenance (TPM) implementation using Overall Equipment Effectiveness (OEE) and six big losses for the effectiveness of maintenance practices in the manufacturing sector. They found the average OEE value for the ring frame machines at PT Apac Inti Corpora was 79.96%. They determined the six major losses impacting machine effectiveness and from the six big losses, the most significant contributor to low OEE was reduced speed losses which comprise 17.303% of the entire loss. Based on their analysis they recommended that to enhance equipment effectiveness: implement autonomous maintenance practices, provide training for operators and maintenance technicians, and increase supervision of operations in the workplace to ensure adherence to the best practices.

(Özcan et al., 2020) the authors present that the process of distinguishing data greatly influences the education of the artificial neural network (ANN). They presented that variations in training and test data groupings can lead to different test results, despite the network structure remaining unchanged. They clearly stated that selecting appropriate datasets for training, and testing is important to improve model performance. They analyzed a total of 285 faults over 11 years, from these 80% (228 faults) are used for training the ANN. The rest 20% (57 faults) was used as the test set. They divided the training into three subsets: 70% for training, 15% for validation, and 15% for testing. They used an iterative process to minimize deviation from target values, which shows a strong approach to model training and evaluation. They also introduced that hydroelectric power plants play a vital role in sustainable energy supply, and the study recommends that maintenance impacts at these facilities are more significant than at wind turbine plants. The authors used an integrating approach using the Analytic Hierarchy Process (AHP), Techniques for Order Preference by similarity to Ideal Solution (TOPSIS), and ANN, which enables in enhancement of analytical capabilities in decision-making processes regarding hydroelectric power plants. From these the AHP method reduces subjectivity and is flexible for combination with other methods, on the other hand, TOPSIS gives an effective ranking method. In addition, they showed that ANN is preferable to traditional prediction methods since it can handle nonlinear problems effectively.

(Rathi et al., 2023) introduced the improvement of productivity and equipment effectiveness of a rolling mill by application of Total Productive Maintenance. They collected six months of data and for the next six months TPM was implemented during their study specifically they analyzed productivity, Mean time between failures (MTBF), Mean Time to repair (MTTR), Equipment Availability, and Overall Equipment Effectiveness (OEE), They obtained 50MT/h productivity which is 10% improvement, 14% improvement in equipment availability, 24.62% improvement in the OEE of from 55.57% to 80.19%, MTTR decreases by 23%, production time increased by 3 hours/day due to reduced breakdowns, and the maintenance cost is significantly reduced. They implemented four TPM pillars these are autonomous maintenance, which involves daily equipment inspection and operator involvement, Focused improvement by using RCA specifically fishbone diagrams, planned maintenance performing scheduled activities like guide changes and roll changes., and the final TPM pillar they implemented was education and training which involves operator up skilling and training. The study shows that the rolling mill OEE moved close to world-class standards (85%after they implemented TPM. In addition, TPM methodology proved effective in minimizing downtime and maximizing production and the study confirmed that structured maintenance programs and employee engagement in maintenance activities are key factors for improving productivity and efficiency.

(Gomaa, 2024) the author investigated whether Lean Six Sigma (LSS) was utilized effectively to shut down maintenance projects. The study developed and used an integrated LSS-DMAIC approach (Define, Measure, Analyze, Improve, and Control) for shutdown maintenance work. Actual performance improvement was achieved: Planned maintenance was improved from 86% to 93%. Operational reliability improved from 72% to 89%. Maintenance process efficiency improved from 62.3% to 69.7%. Bearing MTBF improved from 7,100 to 7,800 hours. MTTR (Mean Time to Repair) bearing decreased from 7 hours to 6 hours. One of the success factors was waste reduction: Utilizing Lean principles (notably the finding wastes DOWNTIME) and 5S techniques, the project reduced non-value-added work by 7.6% (37.7% to 30.1%). Root Cause Analysis and FMEA aided in targeting essential improvements:

Systematic analysis (Why-Why, Fishbone, and FMEA) outlined key failure locations (e.g., pump bearing failure) and helped in revising Preventive Maintenance (PM) programs. A culture of ongoing improvement was promoted: The training was supplemented by studying, standardizing, and controlling processes to retain and accumulate benefits gained. More detailed recommendations for future research: Application of this method to high-value-product machinery and longer time frames for data collection to establish long-term effectiveness is suggested in the study.

(Ogubuike Kingsley & E, n.d.) The authors focus on the measurement of Overall Equipment Effectiveness (OEE) in a gas recycling plant, emphasizing performance efficiency, availability, and quality rate as part of an attempt to achieve the highest level of production systems' capacity. They captured low Overall Equipment Effectiveness (OEE); the maximum OEE reading captured was 8.9%, which manifestly shows that the current maintenance strategy is not far from being unsatisfactory. The study found that no maintenance practice was being followed, based on the Plan Do Check Act (PDCA) system, and that this had achieved low failure and equipment downtime levels. Ineffective and poor equipment caused economic losses in the oil and gas industry by leading to equipment obsolescence, unavailability of spare parts, and unavailability of trained personnel. Plant equipment availability levels lagged the industry benchmark of 90% and thus, indicated room for improvement in equipment reliability and maintenance practice. The research proved the use of TPM to achieve equipment availability and maintenance operator commitment and thereby equipment performance improvement. Five years' trends in the Kwale gas recycling plant's equipment failure and downtime provided room for possible improvement. The study verifies the implementation of the PDCA model to increase maintenance, reduce downtime, and plant reliability and performance.

2.8 Conceptual Model

The research conceptual mode claims the implementation of total productive maintenance alongside Root Cause Analysis enhances the overall equipment of the Melka Wakena hydroelectric power plant. The model shows TPM and RCA are the independent variables, and OEE is the dependent variable.

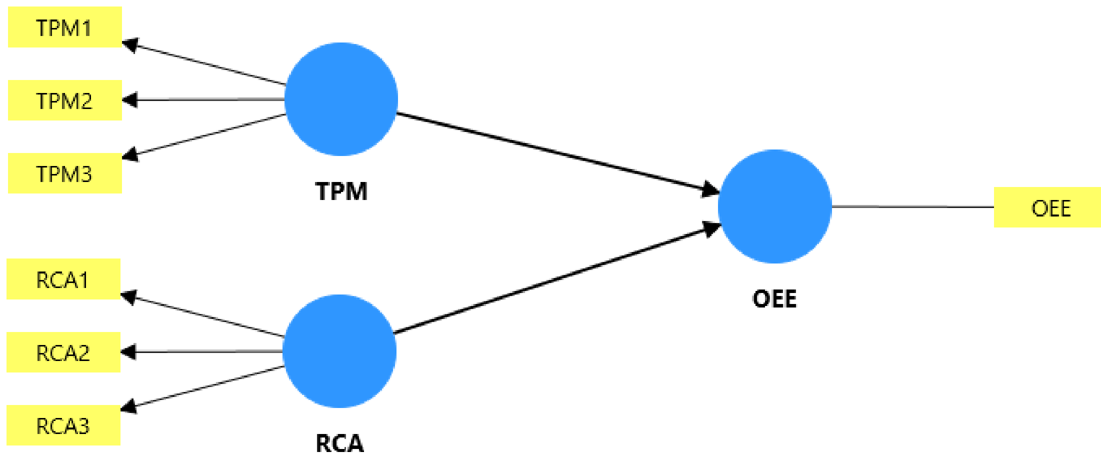

Figure 2.4 Research Conceptual Model

2.9 Research Gap

There have been many researchers conducted on total productive maintenance and overall equipment effectiveness concerning the impact of one on another. Especially researchers have done on the improvement of overall equipment effectiveness through TPM in manufacturing industries. And some of the researchers have done it with the combination of root cause analysis to obtain better overall equipment effectiveness in various industries. Such research is necessary for hydroelectric power plants since the concept of TPM is highly relevant for this sector. Intensive investigations have been done on industries' OEE improvement through TPM and RCA to solve factory maintenance-related problems. However limited reports are available in Ethiopian Power Plants including Melka Wakena HEPP regarding proactive maintenance practices which positively impact the plant OEE improvement by TPM and RCA. This study proposes to investigate the root cause of failures and inefficiency of the power plant and gives appropriate solutions for the acquired problems. The overall equipment effectiveness of the power plant will be enhanced through root cause analysis and TPM.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Methodology

The most critical research tools that will be used to gain pertinent information about the application of TPM and OEE from the Ethiopian electric power generation, the Melka Wakena Hydroelectric Power Plant is observation of the process of production, monitoring equipment, data collected from historical logs, questionnaire, and interviewing. While conducting the interview, there will be unique questions administered by the plant manager, maintenance manager, operation manager, operators, and maintenance workers. The secondary data will be collected from annual reports and records available, including the downtime, total production, daily or monthly faults, and non-productive hours count. Obtaining the OEE values will be step one in the calculation process and it's all about collecting data for availability, performance, and quality.

The most significant failures in availability, performance, and quality are then identified from the six big losses. The availability factor is comprised of setup and adjustment losses, breakdown losses, and losses due to idleness. The performance factor consists of yield or scrap losses, rework losses, minor stoppage, and slowed-speed losses. The TPM method and the RCA tools will be used to address the problem of low values of OEE below the world standards. The approach set its emphasis on six major widely applied factors of lowering the efficiency of the machine.

3.2 Data Collection and Analysis

Data collection was the central step to acquire the current status of operational units of power plants and to study the maintenance practices that are performed in the plant. To continue with this recent credible data were necessary that need to be collected. To do that, it was necessary to oversee the production process of energy under the real running of working units and have proper knowledge about the operation of the hydroelectric power plant. Hence it was crucial to be familiar with the hydroelectric plant running reality and their working and maintenance culture. In addition, It was essential to research comparable works to establish gaps and fill such gaps through a detailed reading of literature like, journal papers and books. After gaining a thorough understanding of hydroelectric power plant and their operating and maintenance procedures the research tools were realized. Thus, primary data were obtained from questionnaires, real-time operating logs, and past data used for research.

3.2.1 Data collected from the questionnaire

Primary data was collected from the Melka Wakena Hydroelectric power plant through a questionnaire targeting knowing the current status of the power plant by TPM and RCA metrics. The targeted groups fall into three categories these are Managers (plant manager, operation manager, and maintenance manager), operators, and maintenance personnel.

The questionnaire was prepared to seek data about TPM and RCA practices in the power plant, to do this we used a total of 20 people including managers. These 20 people are grouped into three to suit our analysis, that is 6 people for unit 1, and 7 people for both unit 3 and unit 4 each.

The question was forwarded to the respondent for each month of the study period which was from July to December 2024 GC.

Questions about TPM were coded as:

TPM1: We perform preventive maintenance regularly

TPM2: Operators are trained to maintain equipment

TPM3: Autonomous Maintenance is implemented

Questions about RCA were coded as:

RCA1: We conduct RCA after equipment breakdown

RCA2: Corrective Measures are taken from RCA

RCA3: RCA is involved in the plant

The 7-point Likert scale was used for rating, 1, 2, 3, 4, 5, 6, and 7 for strongly disagree, disagree, somewhat disagree, neutral, somewhat agree, agree, and strongly agree respectively.

Table 3.1: Collected data from the questionnaire

ID	TPM1	TPM2	TPM3	RCA1	RCA2	RCA3	Unit
P1	4	3	3	4	3	3	U1
P2	3	2	4	3	3	2	U 1
P3	2	3	4	3	3	3	U 1
P4	6	5	5	6	5	5	U 1
P5	4	4	5	4	5	5	U 1
P6	4	4	3	3	4	5	U 3

P7	5	3	4	5	3	4	U 3
P8	3	3	4	3	3	4	U 3
P9	2	3	3	2	3	2	U 3
P10	3	3	4	4	3	2	U 3
P11	4	3	4	4	4	3	U 3
P12	6	5	5	5	5	6	U 3
P13	4	5	4	4	4	5	U 3
P14	4	3	3	2	3	2	U 4
P15	3	2	3	3	2	2	U 4
P16	5	4	3	4	5	3	U 4
P17	3	4	2	3	4	2	U 4
P18	4	2	2	2	3	2	U 4
P19	5	3	4	4	5	3	U 4
P20	4	5	3	5	3	3	U 4

The average score was taken across the three units for six months to see the effect of TPM and RCA on the OEE. This average data was then analyzed using Partial Least Square Structural Equation Modeling (PLS-SEM) which was chosen for its advantage in handling small sample sizes hence, for this analysis, we used SmartPLS 4 software. PLS-SEM is a highly utilized multivariate data analysis technique with a tremendous capability to deal with small samples, and that is why it is going to be employed for data analysis. Besides, PLS-SEM is the appropriate method even when the research object does not have a solid theoretical foundation, particularly when there is little previous knowledge of causal relationships. Unlike CB-SEM and multi-linear regression analysis, PLS-SEM does not require a large sample size, a specific assumption about the data distribution, or even missing data. Researchers with limited data and no theoretical foundation to conduct research can employ PLS-SEM to examine causality relationships. The PLS-SEM algorithm is different from traditional structural equation modeling (SEM) under maximum likelihood. Whenever sample size in research and distribution of data is suitable for utilization by a conventional SEM, there is a practical benefit of using PLS-SEM. The biggest advantage of PLS-SEM is it can handle highly no-normal data.

Table 3.2: Average collected data over six months

Unit	Month	TPM1	TPM2	TPM3	RCA1	RCA2	RCA3	OEE
1	July	3.83	3.5	4	3.83	3.80	3.82	0.44
1	August	3.81	3.51	4.1	3.81	3.82	4	0.29
1	September	3.82	3.52	4.2	3.82	3.83	3.81	0.28
1	October	3.83	3.49	4.1	3.80	3.84	3.83	0.76
1	November	3.80	3.53	4.2	3.79	3.81	3.82	0.64
1	December	3.82	3.48	4.3	3.84	3.79	3.80	0.66
3	July	3.66	3.5	4	3.85	3.57	3.71	0.69
3	August	3.65	3.51	4.1	3.86	3.58	3.72	0.51
3	September	3.67	3.52	4.2	3.84	3.56	3.70	0.16
3	October	3.64	3.53	4.3	3.87	3.55	3.73	0.34
3	November	3.67	3.50	4.2	3.85	3.59	3.74	0.52
3	December	3.65	3.52	4.2	3.86	3.58	3.72	0.77
4	July	4	3.28	3	3.28	3.57	2.42	0.61
4	August	4.1	3.24	3.1	3.23	3.54	2.41	0.47
4	September	4.2	3.25	3.2	3.24	3.53	2.42	0.39
4	October	4.3	3.26	3.3	3.25	3.55	2.43	0.6
4	November	4.4	3.27	3.1	3.26	3.54	2.44	0.52
4	December	4.1	3.28	3	3.27	3.58	2.45	0.69

Then the data obtained by questionnaire was processed and analyzed through PLS-SEM.

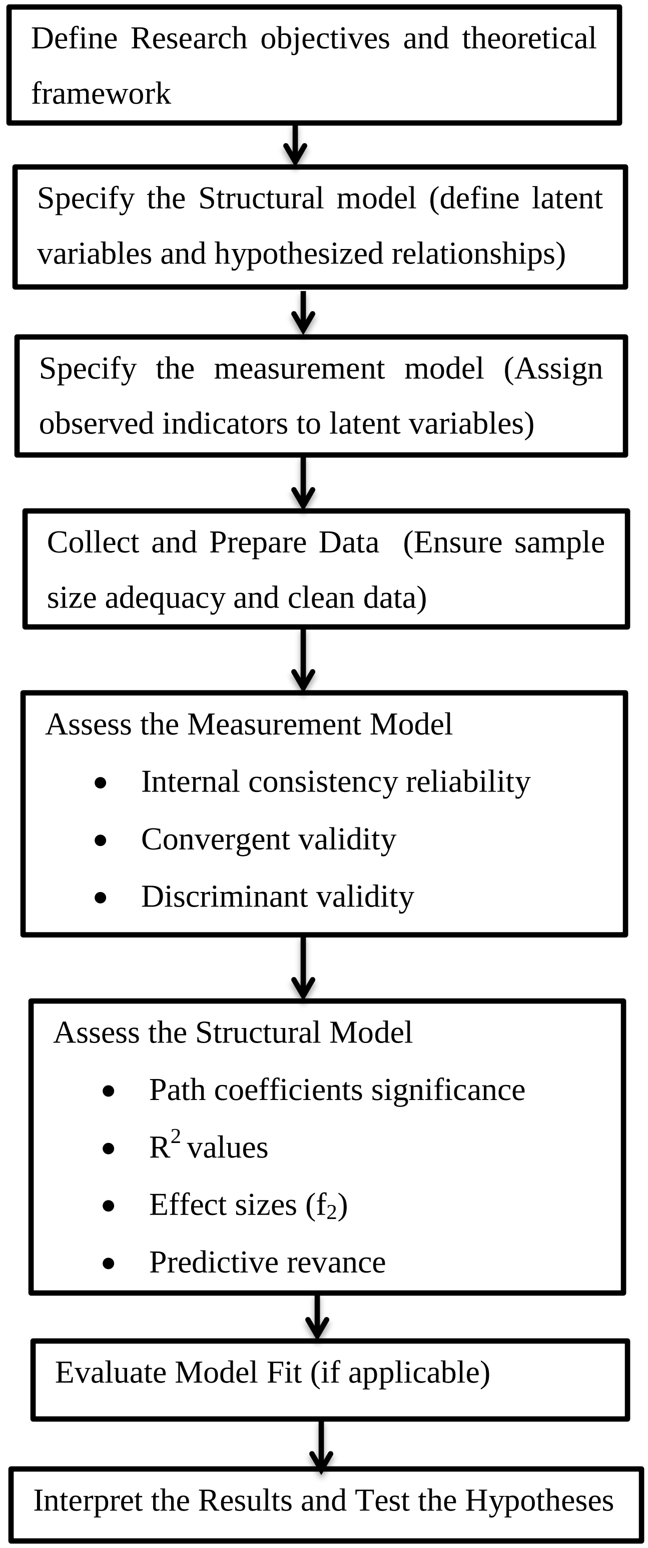

Figure 3.1 Flow Chart of PLS-SEM Analysis

3.2.2 Data Collected Through Historical Logs

The following data were collected from historical data logs of the operation and maintenance department of the power plant. These are:

1. Actual and Planned production
2. Planned and Forced outage
3. Reasons for interruption for the forced outages

These data were collected and organized in a proper format to suit the analysis and interpretation. So these three collected data will be presented and analyzed through the following sections. For clarity, the analysis was also done after the collected data was presented for each available collected data separately.

3.2.3 Collected Planned and Actual Monthly Production of the Plant

Table 3.3: Collected Planned and Actual Monthly production of the plant for six months

Month	**Planned Production** (KWh)	**Actual Production** (KWh)	**Loss** (KWh)
July	32,759,906	40,115,000	7,355,094
August	35,442,975	30,556,000	-4,886,975
September	44,811,493	23,546,000	-21,265,493
October	44,787,642	34,888,000	-9,899,642
November	40,360,289	40,940,000	579,711
December	40,586,168	52,530,000	11,943,832
Total(KWh)	238,748,473	222,575,000	-16,173,473

This report is collected for the half budget year of the power production of the Melka Wakena hydroelectric power plant and this data can be used for the investigation of the potential problem that cause the reduction of power production from the planned production.

Also, it can help with realistic planning of the monthly as well as yearly power production of the power plant.

3.2.4 Planned and Forced Downtime of the Power Plant

Table 3.4: Monthly Planned and Forced Downtime of the Power Plant

Month	Forced Outage (Hrs.)			Total (Hrs.)	Planned outage (Hrs.)			Total (Hrs.)
Units	Unit 1	Unit 3	Unit 4	Unit 1-4	Unit 1	Unit 3	Unit 4	Unit 1-4
July	2	0	0	2	463	90	14	567
August	157	80	72	309	305	282	0	587
September	0	6	0	6	582	461	0	1043
October	0	1	0	1	300	273	0	573
November	29	23	19	71	158	75	0	233
December	5	13	19	37	152	0	68	220
Total (Hrs.)	193	123	110	426	1989	1181	82	3253

3.2.5 Calculation of Six Big Losses of the Power Plant

Steps to Calculate Six Big Losses

1. Determine the Categories

Six Big Losses are grouped under three categories of OEE:

- Availability Losses: Machine Failures, Setup & Adjustments
- Performance Losses: Minor Stoppages & Idling, Slowing Down
- Quality Losses: Process Defects, Reduced Yield

2. Obtain the Correct Data

The data required are:

- Forced and planned outage hours by unit
- Actual vs. rated turbine output
- Number and frequency of small stops or slowdowns
- Energy rejection or grid curtailment events
- Shutdown ramp-up times

3. Calculate the Numbers

A. Equipment Failures (Unplanned Downtime)

$$Loss = Forced\ Outage\ Hours \times Rated\ MW$$

B. Setup and Adjustments (Planned Downtime)

$$Loss = Planned\ Outage\ Hours \times Rated\ MW$$

C. Idling and Minor Stops

Estimate - based logs.

D. Reduced Speed

$$Loss = (Rated\ Output - Actual\ Output) \times Running\ Time$$

E. Process Defects

Add energy not absorbed by the grid due to frequency or voltage mismatch.

F. Reduced Yield

$$Startup\ losses = Startup\ Time \times Rated\ Output \times Number\ of\ Startups$$

The six big losses are grouped under the three main OEE metrics, availability, performance, and quality. To this extent, table 7 shows the categories of six big losses under OEE factors with their description.

Table 3.5: Categories of Six Big Losses

OEE Factor	Type of Loss	Description
Availability	Machine Failures	Unplanned downtime: breakdowns, emergency shutdowns
Availability	Setup & Adjustments	Planned downtime: inspections, adjustments, warm-up, and silt clearing
Performance	Idling & Minor Stops	Short, frequent stoppages (operator reset, turbine delay, sensor miss-readings)
Performance	Reduced Speed	Running below design output or rated capacity (for example, 30MW rather than 38.25MW)
Quality	Process Defects	Energy rejected due to grid incompatibility (voltage, frequency, etc.)
Quality	Reduced Yield	Energy wasted during startup or post-failure ramp-up

3.2.6 Reasons for an interruption for the forced outages

This data was obtained from the monthly failure report of the operation department that was recorded during real-time operation interruption incidents.

Table 3.6:Forced Outages of the Power Plant and causes of interruption

Month	Unit No	Cause of Interruption
July	Unit 1	Under Excitation Voltage
August	Unit 1,3,4	The Forebay was filled by siltation & it’s not possible to purge immediately then the penstock sucks the air.
September	Unit 3	Excitation loss and phase unbalance
		Partial shutdown in case of voltage
		Excitation main feeder trip (excitation loss)
October	Unit 3	Due to overvoltage
November	Unit 4	Phase unbalance
		Governor's excessive oil leakage
	Unit 4	Total shutdown (blackout)
	Unit 3	Due to under excitation (it was not cleared for a long time)
December	Unit 1,3,4	Plant total shutdown due to unit no 4 governor pump failure (unit 4 served as a station service provider for the plant)
	Unit 4	Excessive water leakage on the spherical valve
	Unit 4	Shear pin broken
		Due to overvoltage
		The cooling pump failed (auxiliary DC supply failed)

3.2.7 Determination of the OEE of the Power Plant

The OEE of the Melka Wakena Hydroelectric Power Plant was calculated by considering the three variables: Availability, Performance, and Quality.

Availability (is the plant running when it should?)

Performance (is the plant running at installed capacity?)

Quality (is the plant generating usable, good energy?)

$$OEE = (Availability \times Performance \times Quality)100$$

1. Availability

Measures the percentage of time the plant was run vs scheduling time.

$$Availability = \frac{\text{Operating Time}}{Planned\ production\ time} \times 100$$

Operating Time = Planned Production Time – Unplanned Downtime (like emergency shutdowns, maintenance, etc.)

2. Performance

Measures how well the plant ran compared to its maximum designed capacity.

$$Performance = \frac{\text{Actual Power output}}{Theoretical\ maximum\ output} \times 100$$

$$\boldsymbol{Actual\ Power\ Output} = Energy\ actually\ generated.$$

$$\boldsymbol{Theoretical\ Output} = Capacity \times Operating\ Time.$$

3. Quality

In manufacturing, "Quality" often mean non-defective units. In a hydroelectric plant, we can define Quality as the percentage of generated electricity that meets grid requirements (e.g., voltage, frequency stability, and absence of forced curtailments).

$$Quality = \frac{\text{Usable Electricity output}}{Total\ Electricity\ output} \times 100$$

In the calculation process, the OEE of all three working units was determined separately for six months and the average value of the plant was taken. Then the calculated value was compared with world-class OEE.

3.2.8 Root cause analysis of inefficiency

To find out the main reason for the failure of the power plant it is necessary to apply some of the root cause analysis tools. This method gives the solution to the failure from its root source that is beneficial in terms of keeping the machinery in fine working condition and saving maintenance costs by avoiding unnecessary spending. One of the RCA tools to be utilized is the application of the Pareto chart to be utilized in prioritizing the most common cause of failure, and the Fishbone diagram will be utilized in identifying the potential cause of the most common cause of failures.

- **Fishbone Diagram:** a graphical brainstorming tool for identifying the potential causes of a problem or problems. Using this tool the potential causes of failures in the case Hydroelectric Power Plant will be analyzed. Alongside this, we used the **5 whys** technique to get deep into the root causes of the identified problem.

- **Pareto Chart:** One specific application of the Pareto chart is equipment breakdown identification. There will be data recorded of each equipment breakdown in a given time frame and the cause they broke down. Those causes will then be categorized into classes that may include bad design, lack of maintenance, operator failure, or external causes. Once the categories have been established, they will be ranked by frequency or severity, and a Pareto chart is created. The chart allows analysts to quickly see which categories are accountable for most of the equipment failures, and prioritize efforts to correct those issues. By focusing on the top handful of categories of equipment failure, the Power plant can reduce downtime, increase OEE, and improve safety.

3.3 Flow Chart of Research Methodology

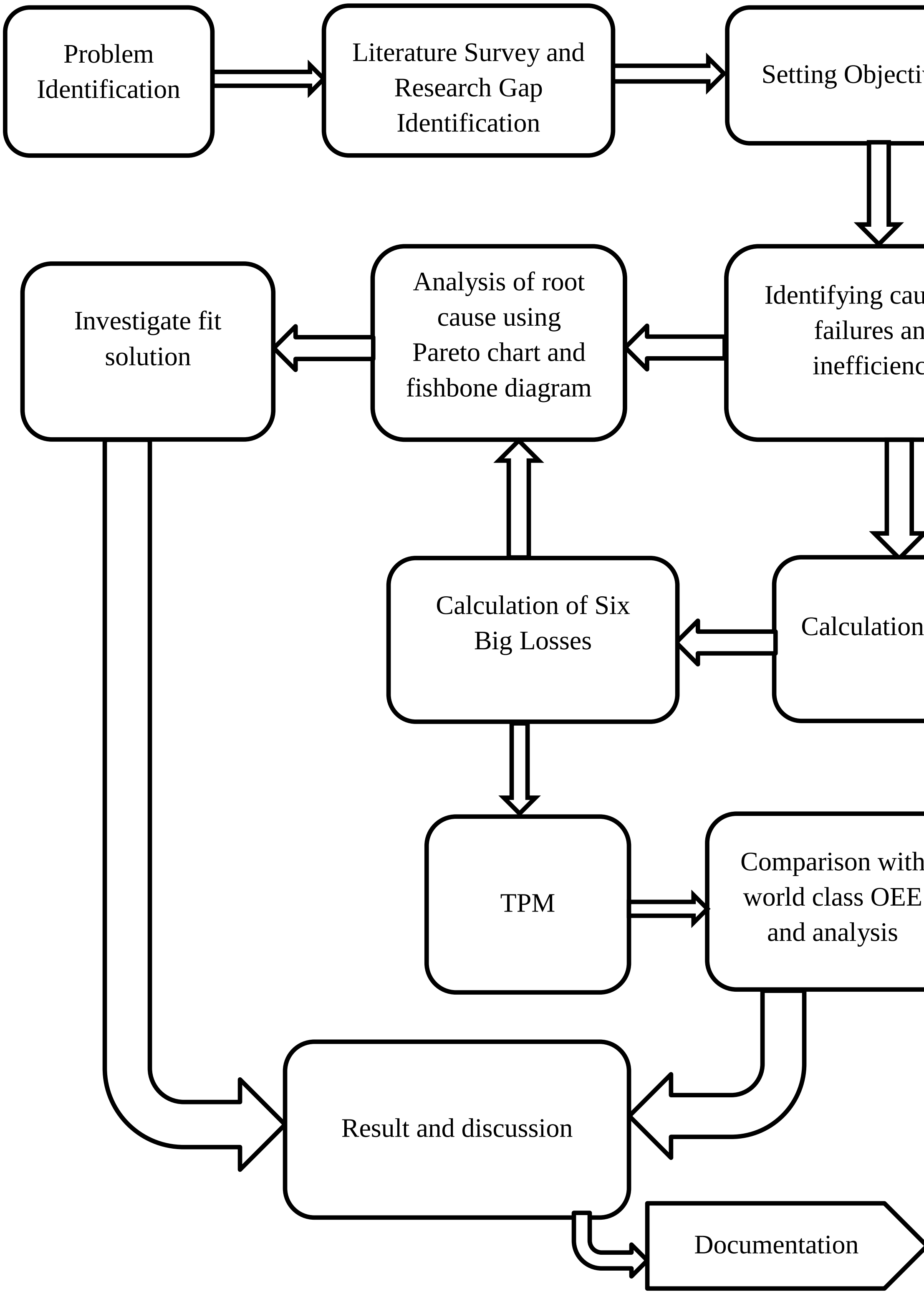

Figure 3.2 Flow Chart of Research Methodology

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 General Overview of Collected Data

Primary data were collected using a questionnaire from the plant manager, operation manager, maintenance manager, operators, and maintenance personnel about the practices of Total Productive Maintenance (TPM) and Root Cause Analysis (RCA) the data were analyzed using Partial Least square Structural Modeling (PLS-SEM) to assess the relationship between TPM practices, the application of RCA tools, and improving OEE.

Secondly, historical logs were collected from the maintenance and operation department of the power plant. From these departments, the collected data includes actual and planned production planned and forced outages, and reasons for interruption for the forced outages. The data collected from these departments were considered six months of the power plant production period. The data were analyzed and interpreted through OEE calculation, six big losses calculation, and RCA tools were used such as a Pareto chart, fishbone diagram, and 5 whys which will be presented throughout the following sections.

4.2 The Impact of Total Productive Maintenance (TPM) and Root Cause Analysis (RCA)

4.2.1 Profile of Respondents and Case Power Plant

The general description data of the respondents includes gender; age, position, and work experience in the case of power plant are shown in Table.

As shown in Table 14, the majority of the respondents (75%) were males, and females were (25%), indicating the participation of females in the study is low. The majority of the respondents (70%) had a first degree, 25% of respondents had a level 5 TVET certificate, and only one person had a master's degree. It was made carefully to include managers, operators, and maintenance personnel to get reliable information about TPM, and RCA practices in the power plant.

Table 4.1: Profile of Respondents

Profile	Category	Number of respondents	% respondents
Gender	Male	15	75
	Female	5	25
Age	26-30	2	10
	31-35	10	50
	36-40	4	20
	>41	4	20
Position	Maintenance personnel	7	35
	Operators	10	50
	Managers	3	15
Work experience	2-5	2	10
	6-10	3	15
	11-15	11	55
	>15	4	20
Education level	Level 5 TVET	5	25
	First Degree	14	70
	Master's Degree	1	5
Company size	Medium		
Company Type	Energy Production		

4.2.2 Responses to the question "Have you practiced Total Productive Maintenance in the power plant"

Most of the respondents (90%) believed that autonomous maintenance was not adopted in their power plant, and only 10% of the respondents believed that it was partially implemented as shown in Figure 18. Based on the responses TPM was not implemented in the plant.

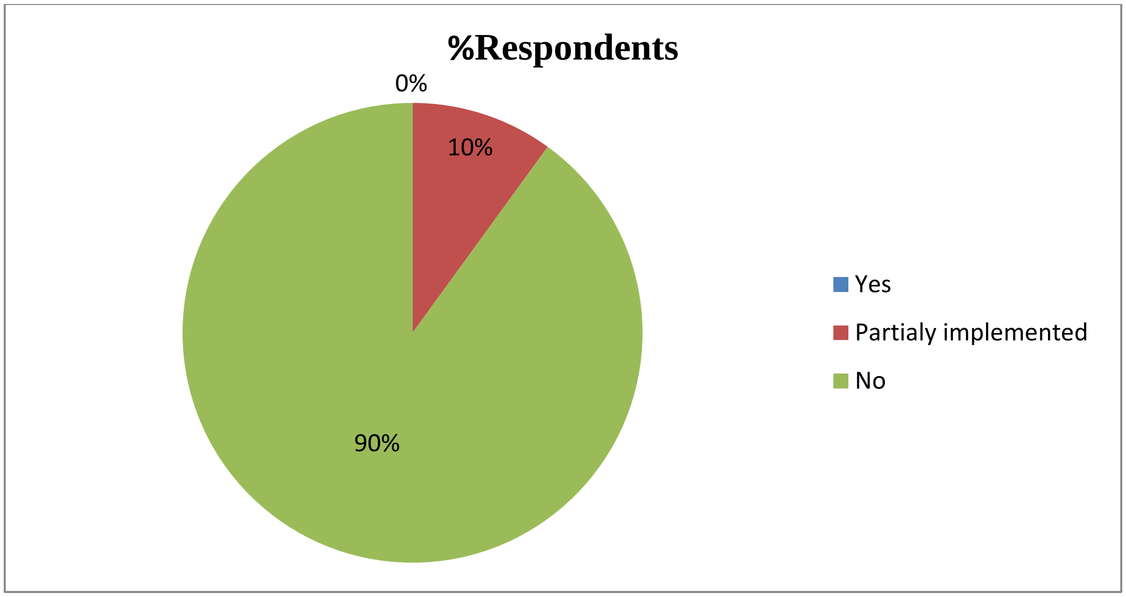

Figure 4.1 Answers "Do you believe Total Productive Maintenance is applied in the power plant?"

4.2.3 Responses to the question "Have you used Root cause analysis in tracking failures in the power plant"

Most of the respondents (70%) believed that RCA was not used in tracking failures in their power plant, 20% of the respondents believed that it was partially implemented, and 10% of respondents believed that it was used as shown in Figure. Based on the responses it is fair to say RCA was not used in tracking failures in the plant.

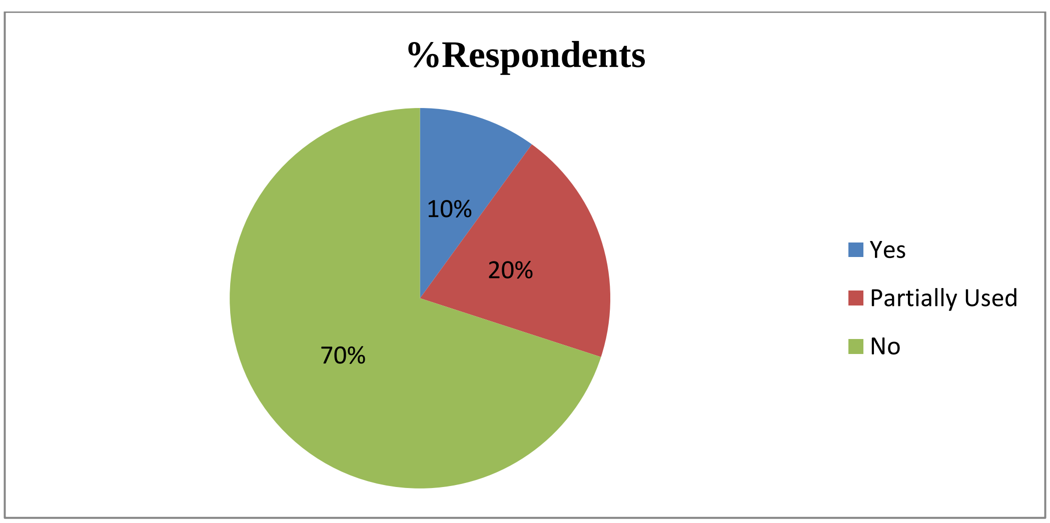

Figure 4.2 Answers to the question "Have you used Root Cause Analysis in tracking failures in the power plant?"

4.2.4 Mean, Standard Deviation, and Correlation

Table 4.2: Mean, and Standard deviation of the responses given related to TPM, and RCA

Name	N	Type	Mean	Standard deviation
Unit	20	CAT	2.667	1.247
TPM1	20	MET	4.009	0.391
TPM2	20	MET	3.588	0.508
TPM3	20	MET	3.867	0.589
RCA1	20	MET	3.716	0.386
RCA2	20	MET	3.756	0.352
RCA3	20	MET	3.434	0.767
OEE	20	MET	0.519	0.171

The descriptive statistics show that while TPM and RCA practices are moderately practiced in the 20 units, OEE is relatively low at 51.9% on average. This reflects that there are underlying issues that limit the effects of maintenance practices, which is further examined in the inferential analysis section. Standard deviations by variables are indicative of moderate response variability, with that of RCA3 showing the most spread, indicating inconstancy of recording or monitoring of RCA results.

Table 4.3: Correlation between TPM, and RCA with OEE

	TPM1	**TPM2**	**TPM3**	**RCA1**	**RCA2**	**RCA3**	**OEE**
TPM1	1.00						
TPM2	0.672	1.00					
TPM3	0.041	0.696	1.00				
RCA1	0.207	0.853	0.920	1.00			

RCA2	0.663	0.939	0.589	0.797	1.00		
RCA3	0.020	0.721	0.912	0.968	0.715	1.00	
OEE	0.508	0.426	0.012	0.201	0.456	0.087	1.00

Correlation analysis shows TPM1 (autonomous maintenance) and RCA2 (corrective action implementation) are the most significant predictors for improved OEE. Training and documentation (TPM3 and RCA3) contribute very little, if anything, directly to performance in this data set, possibly because implementation was ineffective. These findings validate the hypothesis and lend support to the use of TPM and RCA as strategic maintenance practices to improve equipment performance.

4.2.5 Evaluation of Measurement Model

After running the PLS-SEM algorithm the relation between the indicators was evaluated (Figure 4.3) the result shows that Crobanch's Alpha value for all constructs was above 0.7 indicating the internal consistency of the measurement model.

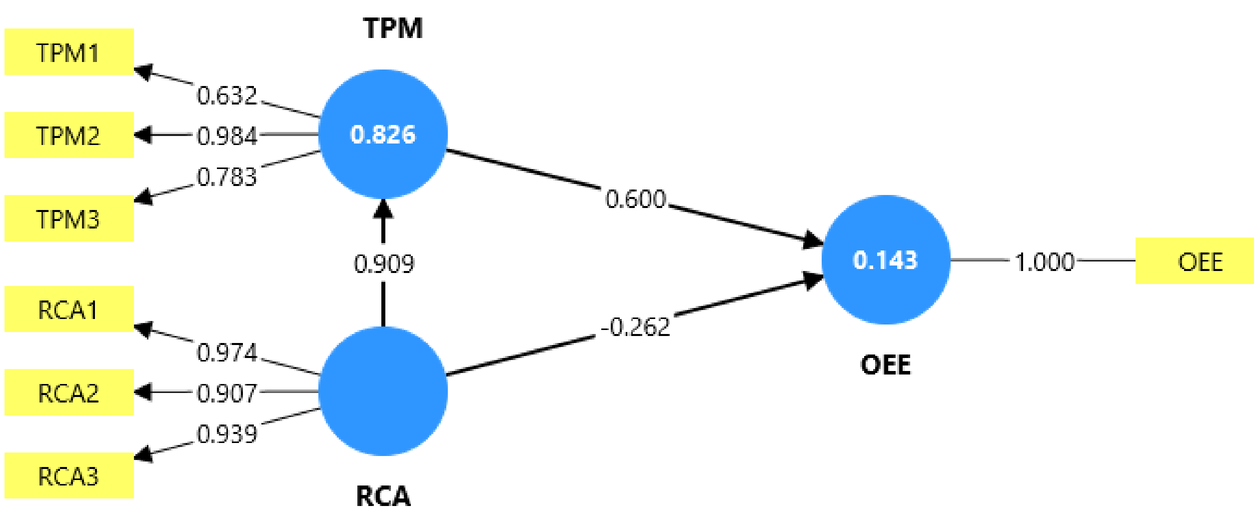

Figure 4.3 PLS-SEM correlations, factor loading values of TPM, RCA, and OEE

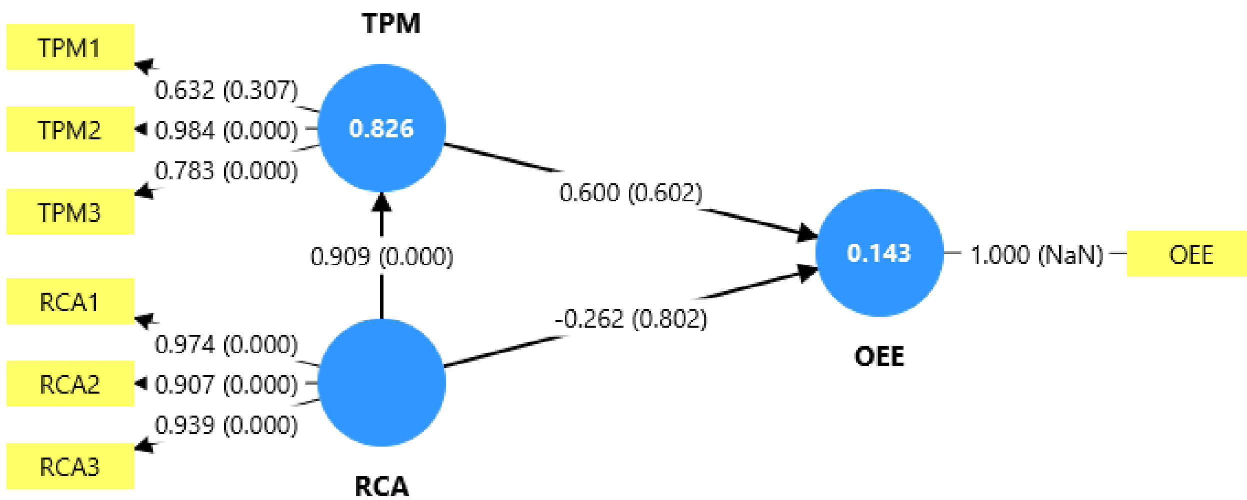

Figure 4.4 Bootstrapping values of RCA, TPM, and OEE (t- t-values)

The discriminant validity was checked and well above 0.5 showing our measurement model was valid which confirms the research conceptual model that TPM and RCA have a positive impact on OEE.

4.3 Monthly Production Performance Analysis

From Table 3.4 the planned and actual production report of the power plant indicates that we can see that there is a difference in the actual and planned production for August and October. But by September, there is a huge reduction in monthly production of the power plant from the planned production.

On the other hand on moth July, November, and December there is an increase in the monthly production of the power plant from the planned production. The monthly production reports indicate that there are months that require special attention and maintenance priority to avoid unnecessary unplanned downtime by recognizing that the season is directly affecting the power plant's operational effectiveness by causing a sudden shutdown of the working units of the power plant.

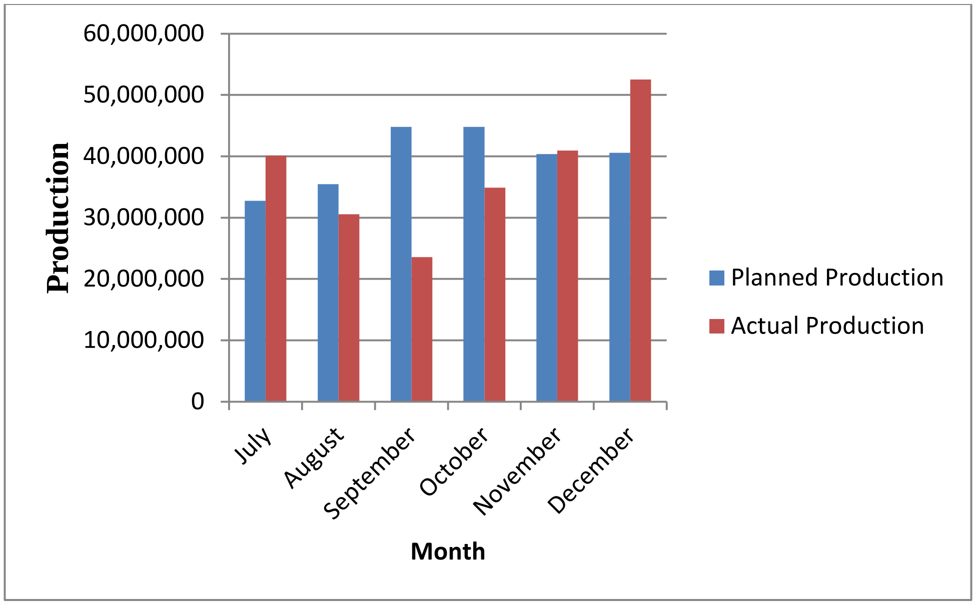

Figure 4.5 Planned and Actual Production of the Power Plant

From Table 3.5 planned and forced downtime of the power plant This data indicates the downtime of the power plant which includes both planned outage and forced outage. So from this data, we can observe that:

- By August, forced outage (309 hours) is very high, indicating that there is a sudden breakdown of the working units occurring without prior planning.
- This trend shows that failures are occurring suddenly and reacting to them which is a sign of reactive maintenance is frequently followed in the power plant.

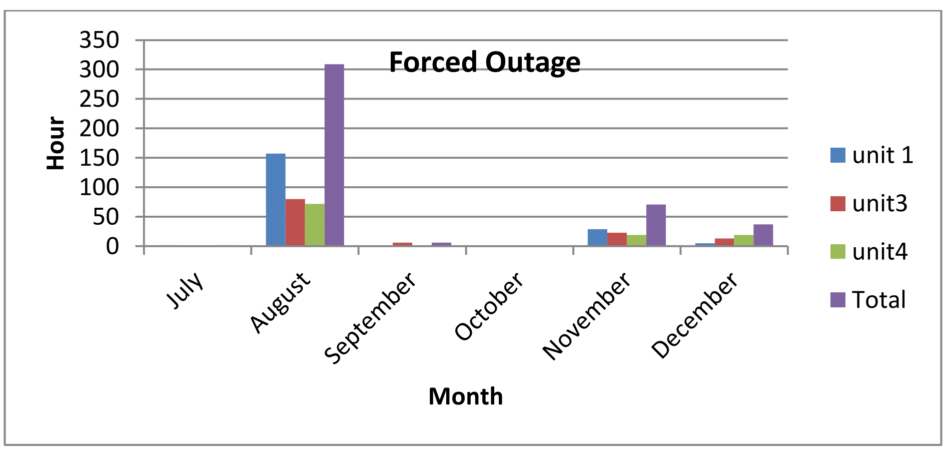

Figure 4.6 Forced Outage Hours per Month in 2024 G.C

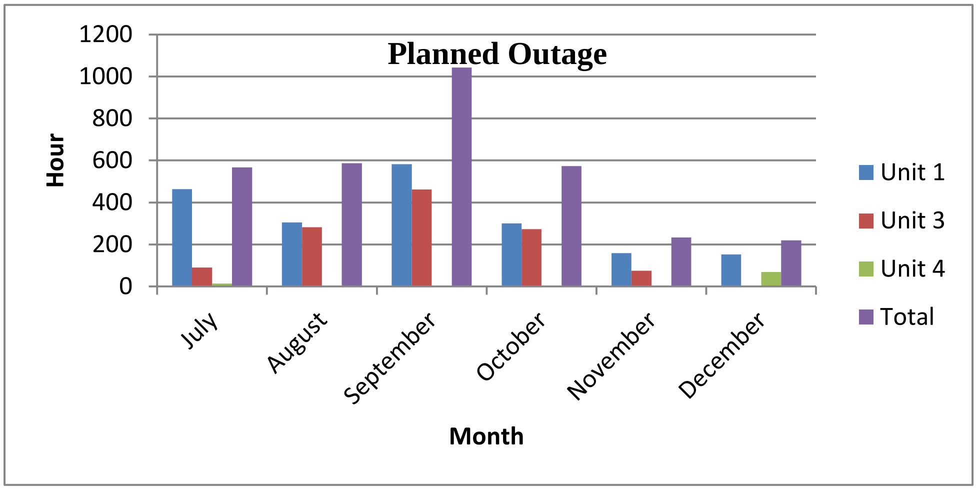

Figure 4.7 Planned Outage Hours per Month in 2024 G.C

- From the data, we can observe that there are uneven maintenance practices since there are varying levels of maintenance downtime. For instance, unit 4 had 0 hours of planned outage in some months but encountered considerable forced outages during August.
- Even though there are planned outages, they are inconsistent throughout all months. For instance, there is no planned outage for Unit 4 in July and September.

4.3.1 Major failures happened in six months

During the six-month study period, the power plant experienced major interruptions that presented significant challenges in getting the plant back up and running (Table 3.6). In August, the plant was on the brink of halting operations completely due to a five-day production stoppage. In August, the power plant faced a severe challenge when it came close to shutting down its operations for five consecutive days. This interruption was just one of the many hurdles encountered during the six-month study period. The plant had to work diligently to restore operations and overcome the obstacles that threatened its functionality. Despite the difficulties encountered throughout the research period, the power plant managed to overcome them and keep running.

The team's perseverance and commitment were crucial in keeping the plant running smoothly and efficiently during the research. The second one was the issue of maintenance practices; there was no routine checking of the powerhouse intake quick closing gate which makes water pass through the penstock. After the failure happen when the gate is tested it was not in its correct place which made it not pass sufficient water in the penstock which in turn caused the Francis turbine to not be surrounded by water, and suck air which stops the whole operation of the working equipment.

Thus, air-sucking led to the rest of the water that flowed through the turbine-generator shaft and filled the machine floor. Here it is stated that there is some problem in the management team, as they could not keep the dam environment free from outside interference by negotiating with farmland owners. Other than these the maintenance practices in power plants have a problem in routine inspection and checking of its assets so that the machinery is always in good working condition.

The causes of interruption can be grouped under Mechanical, Electrical, and System fluctuation (External factor).

4.4 Six Big Losses Analysis

The calculation was done based on the data collected from the historical logs, downtime reports, the current and installed capacity of the power plant, and real-time operation observation to see the startup loss duration, the time taken to start one working unit was 15 minutes until it is synchronized with the grid and begin to supplying required energy by the system. The shutdown process also takes 15 minutes until the turbine stops. Each loss is presented in the form of a megawatt-hour (MWh).

Representation of losses in the table

1. Equipment Failures (Unplanned Downtime)
2. Setup and Adjustments (Planned Downtime
3. Idling and Minor Stops
4. Reduced Speed
5. Process Defects
6. Reduced Yield

We have used this portrayal to make the appearance of the table easier so there is no other motive of giving further implication.

Table 4.4: Six big loss values of working units of the power plant

Months	Unit 1						Unit 3						Unit 4					
	Six Big Losses (MWh)						Six Big Losses (MWh						Six Big Losses (MWh					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
July	76.25	17709.75	292.61	2613.75	90	191.25	0	3442.25	722.92	5197.5	60	153	0	535.5	810.15	5940	87.5	0
August	6005.25	11666.2	296.25	2644.5	60	286.87	3060	10786.5	410.805	2953.5	64	191.25	2754		743.38	5346	94.5	191.25
September	0	22261.5	158.35	1414.5	87	1035	229.5	178633.25	290.31	2087.25	62	2087.75	0	0	826.2	5940	87	0
October	0	11475	481.95	481.95	60	191.25	38.25	10442.25	511.78	3679.5	68	191.25	0	0	826.2	5940	88.5	0
November	11009.25	6043.5	611.61	5463.25	69	153	879.75	2868.75	713.74	5131.5	78	95.62	726.75	0	803.25	5783.25	74.75	66.93
December	191.25	5814	646.04	5770.75	72	153	4322.25	0	811.25	5832.75	70	57.37	726.75	2601	726.36	5222.25	84	66.93
Total (MWh)	17282	74970	2486.81	18388.7	438	2010.37	8529.75	206173.0	3460.805	24882	402	2776.24	4207.5	3136.5	4735.54	34171.5	516.25	325.11

Table 4.4 shows the calculation of six major losses of the working units of the power plant each unit's losses are presented in MWh by taking respective data from operational monthly downtime reports for six consecutive months. Each loss category of the working units is then summed up to see the overall effect of losses on the entire plant. This determination of losses is used for identifying the root causes of failure and inefficiency of the power plant.

Table 4.5: Total losses of working units through six months

Losses	Unit 1(MWh)	Unit 3 (MWh)	Unit 4 (MWh)	Total(MWh)
Equipment Failures (Unplanned Downtime)	17282	8529.75	4207.5	30019.25
Setup and Adjustments (Planned Downtime)	74970	206173.005	3136.5	284279.50
Idling and Minor Stops	2486.81	3460.805	4735.54	10683.15
Reduced Speed	18388.7	24882	34171.5	77442.2
Process Defects	438	402	516.25	1356.25
Reduced Yield	2010.37	2776.24	325.11	5111.72

Table 4.5 shows the total losses of the three working units of the power plant that is 30019.25MWh lost due to Equipment failure, 284279.50 MWh in planned downtime can be considered as setup and adjustments loss, 10683.15 MWh in Idling and minor stops, 77442.20 MWh in reduced speed which indicates the reduction of capacity of the working unis from their rated power output.

Table 4.6: Collected total losses of the power plant

Losses	Total losses(MWh)	Percentage	Cumulative Percentage
Setup and Adjustments (Planned Downtime)	284279.50	69.52%	69.52%
Reduced Speed	77442.2	18.94%	88.46%
Equipment Failures (Unplanned Downtime)	30019.25	7.34%	95.81%

Idling and Minor Stops	10683.15	2.61%	98.42%
Reduced Yield	5111.72	1.25%	99.67%
Process Defects	1356.25	0.33%	100.00%

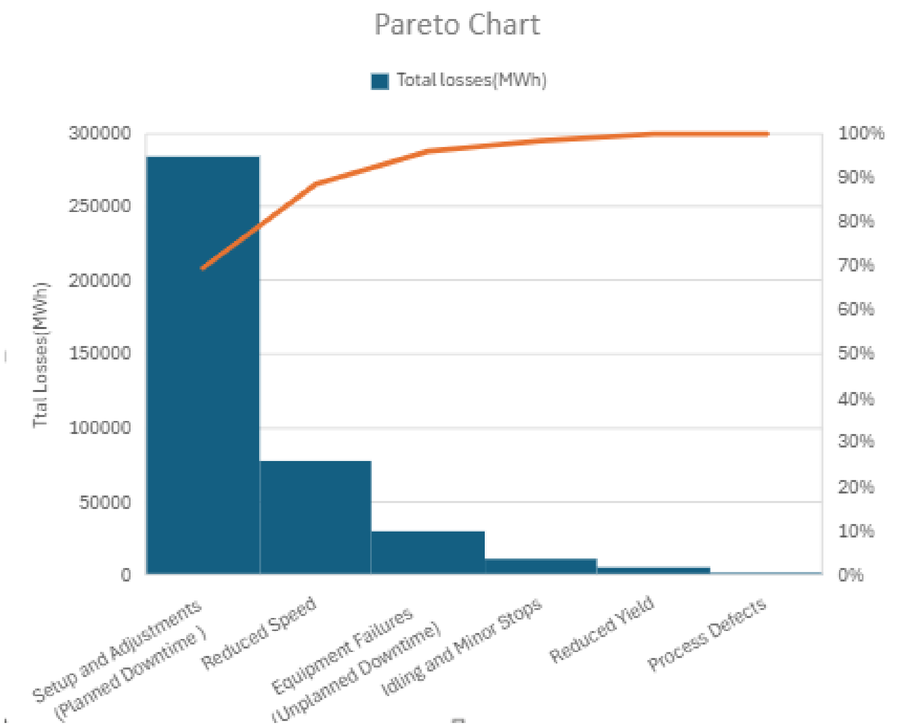

Figure 4.8 Analysis of Total Losses with Pareto Chart

The analysis of the Six Big Losses at Melka Wakena Hydroelectric Power Plant can provide important information in terms of operational inefficiencies that negatively affect Overall Equipment Effectiveness (OEE). It has been shown that Setup and Adjustments (Planned Downtime) are the most significant source of total energy losses 69.52%, or (284,279.50 MWh). Due to maintenance, switchovers, and operational readjustments, the plant is undergoing extended or repeated planned shutdowns. Better scheduling, more frequent and suitable planning, improved maintenance practices, and implementation of planned maintenance under TPM can all minimize this downtime significantly. The second largest loss category, Reduced Speed, is at 18. 94% (2074422.2MWh) of total losses reflects the potential that either the turbines or auxiliary system may be operating at a lower speed from either variable load sources, flow variations, or operating performance deficiencies. One of the methods to tackle these challenges may be the optimization of the control systems, tuning of operating parameters, and training to achieve the highest speed.

Equipment Failure (Unplanned Downtime) causes 7.34% (30,019.25MWh) loss. Even though not the most frequent loss category during this phase but reflective of the need for preventive and predictive maintenance intervention. Equipment failure not only stops production but also increases repair expenses and the likelihood of secondary damage. Implementation of Autonomous Maintenance, condition monitoring, and proper Root Cause Analysis (RCA) can avoid such failures and prolong equipment life. Minor contributors like Idling and Minor Stops (2.61%), Reduced Yield (1.25%), and Process Defects (0.33%) are yet areas where the scope for improvement can be made since, though not individually summing up to doing a great deal in lost MWh, they may sometimes be indicative of hidden general inefficiencies in operation, process stability or quality control which could be addressable through training, standard operating procedure (SOP) discipline, and visual control.

Summary of the loss analysis This report discovers, that an attempt to concentrate improvement activities on Planned Downtime and Reduced Speed (88. 46% of total losses) will optimize OEE the most. The results also determined the significance of Total Productive Maintenance (TPM) practices (Planned Maintenance, Focused Improvement, and Training and Education) towards sustaining performance improvement in the factory.

Table 4.7: Collected Downtime of Equipment

Equipment	Total downtime(Hrs.)	Percentage	Cumulative Percentage
Cooling water pump	240	38.59%	38.59%
Excitation System	214	34.41%	72.99%
Governor oil pump	60	9.65%	82.64%
Main Inlet valve	50	8.04%	90.68%
Trickled Oil Pump	38	6.11%	96.78%
Air Compressor	20	3.22%	100.00%

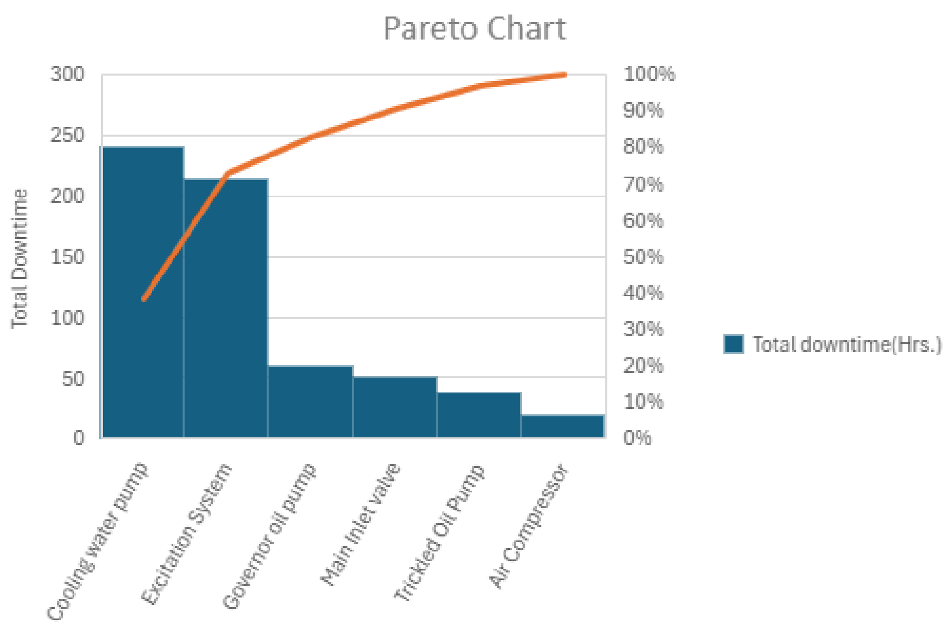

Figure 4.7

Figure 4.9: Downtime analysis with Pareto Chart

To determine and decide what corrective measures to these major problematic types of equipment, we will perform a Pareto chart analysis on these types of equipment.

During my 6 month study period, I observed that there were redundant maintenance works that were done without any significant maintenance planning. Specifically, the cooling system that works with water has more failures at the cooling water pump. The cooling pump fails frequently, making the plant for extra costs to maintain the equipment.

Causes of Cooling Pump Failures

- Lack of spare parts
- Shaft failure due to overheating and vibration
- Flange coupling failure
- Motor functional failure
- Bearing failure by excessive Vibration

Figure 4.10 shows the main Causes of Cooling Pump Failures which account for approximately 80% of the total cooling water pump downtime.

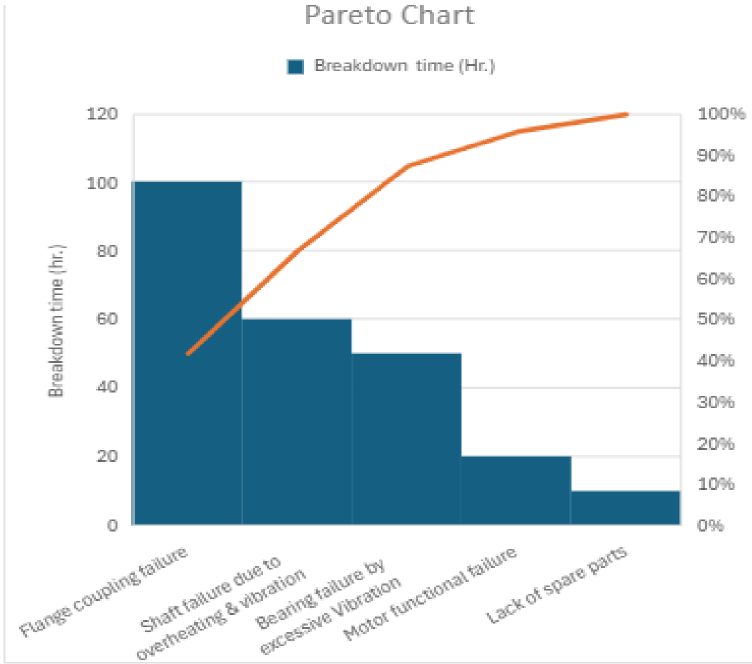

Figure 4.10 Causes of Cooling Pump Failures

From the chart, approximately 80% of cooling pump failures was caused by flange coupling failure.

4.5 OEE Analysis

The OEE of the Melka Wakena Hydroelectric Power Plant was calculated by considering the three variables: Availability, Performance, and Quality. To do this the monthly production, planed and forced down time, startup and shut down times, and the installed capacity vs current capacity of the working units were used for the determination of OEE of each units through the six month study period.

1. Availability

Measures the percentage of time the plant was run vs scheduling time.

$$Availability = \frac{\text{Operating Time}}{Planned\ production\ time} \times 100$$

Operating Time = Planned Production Time – Unplanned Downtime (like emergency shutdowns, maintenance, etc.)

2. Performance

Measures how well the plant ran compared to its maximum designed capacity.

$$Performance = \frac{\text{Actual Power output}}{Theoretical\ maximum\ output} \times 100$$

$$\boldsymbol{Actual\ Power\ Output}\ =\ Energy\ actually\ generated.$$

$$\boldsymbol{Theoretical\ Output}\ =\ Capacity\ \times\ Operating\ Time.$$

3. Quality

In manufacturing, "Quality" often mean non-defective units. In a hydroelectric plant, we can define Quality as the percentage of generated electricity that meets grid requirements (e.g., voltage, frequency stability, and absence of forced curtailments).

$$Quality = \frac{\text{Usable Electricity output}}{Total\ Electricity\ output} \times 100$$

By performing this calculation the following table was generated.

Table 4.8: OEE of Melka Wakena Hydroelectric Power Plant

Unit	Month						Plant OEE (%)
	July	August	September	October	November	December	
Unit 1	44.41	29.38	28.17	76.18	64.19	66	55
Unit 3	69.7	51.61	16.62	34.05	52.49	77.7	
Unit 4	69	61.29	72.94	71.33	40.79	64.28	
Average	61.03	47.42	39.24	60.52	52.49	69.32	

So the Melka Wakena hydroelectric power has an average OEE value of 55% based on a six-month study at the plant. This OEE value is well below the world-class OEE which is 85%, hence the plant's OEE value has to be enhanced in the study undertaking it. The maintenance strategy needs a good look to improve the OEE of the plant.

During the OEE measurement of each working unit from the three factors of OEE which are availability, performance, and quality, performance was very low which significantly decreased the OEE of these working units. For this performance loss, the reduction of working unit capacity from the installing to actual working power was responsible, since the actual capacity of units 1, unit 3, and unit 4 are 25 MW, 30 MW, and 30 MW respectively although their installing capacity was 38.25MW each. Six-month OEE comparison of Units 1, 3, and 4 registered variables and low average effectiveness percentage. The average OEE value calculated was far below the world-class benchmark level of 85% indicating a colossal room for improvement. Actual availability, performance, and quality rate values were also found to be considerably different in the three units, with the most frequent forced outages and lowest efficiency being experienced by Unit 4. The system was performing less than optimally when it was operating at a capacity of only 25 MW, which was less than the optimal capacity of 38.25 MW. The quality reductions were minimal but were accompanied by considerable episodes of energy rejection due to grid frequency fluctuations.

4.6 Root Cause Analysis Using Fishbone Diagram and 5 Whys

4.6.1 Root Cause Analysis for Low OEE

To identify the major causes of low Overall Equipment Effectiveness (OEE) at the Melka Wakena Hydroelectric Power Plant, a Fishbone Diagram was developed. The data used for the development of this diagram was from maintenance records, interviews, and major interruption happened during six month study period. The diagram categorizes the primary contributors to performance loss under six major causes: Equipment, Methods, Personnel, Measurement, Materials, and Environment. Each category represents a potential source of inefficiencies that restrict optimal equipment performance.

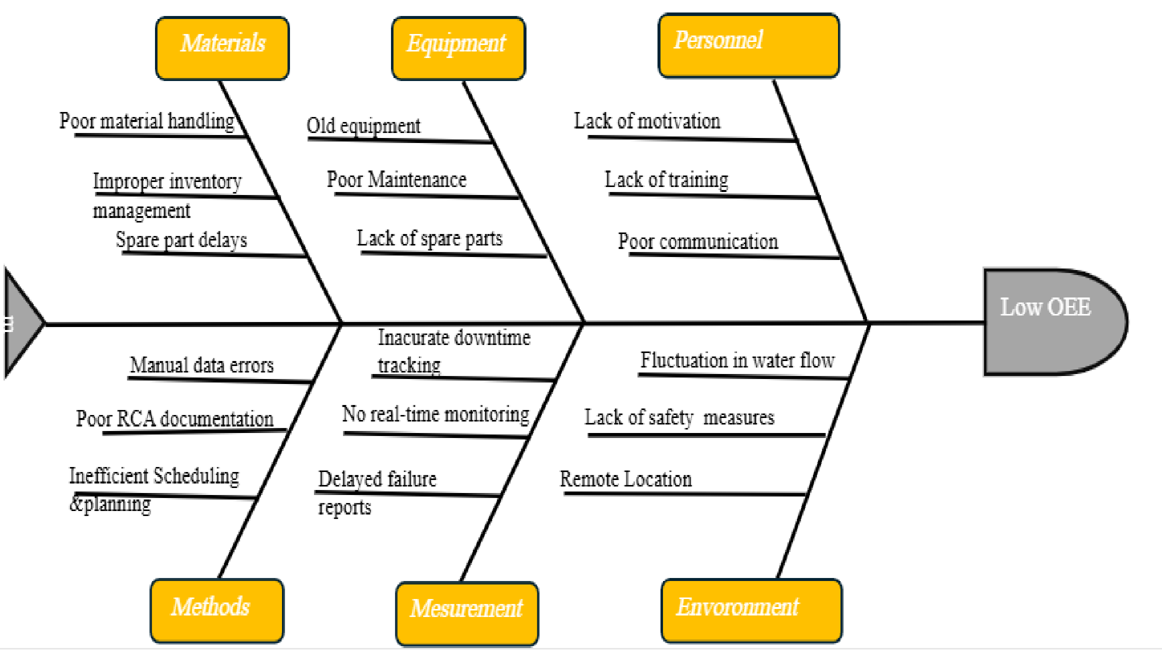

Figure 4.11 Fishbone Diagram for Low OEE

The following descriptions of the root causes were identified.

1. Equipment

Equipment failures are a major contributor to the reduction of OEE. At Melka Wakena, aging turbines and generators were frequently subject to breakdowns due to wear and aged components. In addition, inadequate lubrication practices contributed to mechanical wear and increased maintenance needs. Operational and maintenance process inefficiencies were also a major cause of performance loss.

2. Methods

Ineffective operational and maintenance procedures were also a major source of performance loss. Inconsistency in procedures among maintenance personnel was brought about by the absence of standardization in maintenance practice. The maintenance operations were previously planned ineffectively, resulting in interference with operational activities or delayed response. Poor documentation of root cause analysis results also hindered the plant from identifying repeat faults. An error was introduced and data quality and decisions were compromised in the future through manual recording in maintenance logs.

3. Personnel

Employees also contributed to equipment reliability. The majority of the employees did not get training in operating and maintaining new equipment. Inadequate communication between operational and maintenance staff resulted in misunderstanding fault severity and response priority. Staff with no definite responsibility also caused avoidance of responsibility, and absenteeism resulted in manpower shortages that hindered planned maintenance activities. Fault reporting and performance measurement also contribute significantly to low OEE.

4. Measurement

There were not always total records of downtime incidents, and hence missing equipment reliability data. In addition, fault reporting late did not provide the possibility for immediate corrective action. Few real-time monitoring systems precluded proactive maintenance, and a lack of key performance indicators precluded monitoring progress and identifying areas that needed to improve.

5. Material

Delays in replacing parts contributed to prolonged equipment failures. Insufficient or inadequate equipment components resulted in recurrent failure in several cases. Inventory management overstocking or depletion of essential commodities was also identified. Further, the longevity and performance of the machine were adversely affected by poor ingredients (lubricants, for example).

6. Environment

Further difficulties were introduced by environmental factors; seasonal variations in water supply reduced the power generation schedule and varied equipment load factors; encroachment on groundwater increased corrosion of metal components and degradation of insulation in electrical system conductors. The remoteness of the Melka Wakena Hydroelectric Power Plant contributes to slow spare part access, challenges in retaining skilled personnel, inadequate communication infrastructure, and high logistics costs.

All of these issues are lowering the overall equipment effectiveness of the equipment on the plant floor, which affects the overall effectiveness of the plant.

For the identified problems we are going to find the root cause by asking for 5 whys for each pattern. The source of this analysis was from the calculation of OEE of the power plant working units (Table 4.8).

A. Equipment: Turbine Generator Breakdowns Frequently

1. Why the low OEE?

   - ✓ Due to the equipment's frequent malfunctions.

2. Why is the equipment malfunctioning so often?

   - ✓ Due to inconsistent performance of preventive maintenance.

3. Why are the irregularities in preventive maintenance?

   - ✓ Due to the low adherence to maintenance schedules.

4. Why aren't the schedules adhered to?

   - ✓ Due to unclear responsibility and a lack of maintenance personnel.

5. Why is there a lack of accountability and a shortage?

- ✓ Because of inadequate management control and workforce planning.

Root Cause: Frequent equipment failures are caused by inadequate maintenance planning and staff allocation.

B. Ineffective Operating Procedures as a Method

1. Why the low OEE?
   - ✓ Due to the inconsistent operation practices.
2. Why is there inconsistency?
   - ✓ Since various shifts adhere to different procedures.
3. Why are shifts conducted differently?
   - ✓ Because of the absence of a standard operating procedure (SOP).
4. Why does the SOP not exist?
   - ✓ Because it was never officially trained or documented.
5. Why wasn't it trained or documented?
   - ✓ Due to the absence of a continuous improvement-oriented quality management system in the plant.

The underlying cause of Performance is inconsistent and inefficient when standard operating procedures are not followed, recorded, and enforced.

C. Insufficient Operator Proficiency

1. Why the low OEE?
   - ✓ Due to the inefficient utilization of the equipment.
2. Why isn't it utilized effectively?
   - ✓ Because operators delay modifications or make mistakes.
3. Why do operators make mistakes?
   - ✓ Due to their inadequate training.
4. Why they are not trained?

- ✓ Due to the lack of an organized program for skill development or training.

5. Why is there no program?

- ✓ Because the plant's operational strategy does not place a high priority on training.

The underlying cause of Operational efficiency is decreased skill gaps caused by a lack of investment in staff development.

D. Inaccurate Performance Monitoring in Measurement

1. Why did the low OEE?

- ✓ Because it is difficult to track actual performance losses.

2. Why aren't they being monitored?

- ✓ Due to the incompleteness or inaccuracy of the data gathered.

3. Why data to be erroneous?

- ✓ Due to the aging and badly calibrated measuring instruments.

4. Why have tools become obsolete?

- ✓ Due to the absence of an instrumentation asset management approach.

5. Why is there a lack of plan?

- ✓ Because planning for operations and maintenance does not incorporate performance measurement.

The Root Cause is inadequate measuring infrastructure results in a dearth of useful information for enhancing equipment performance.

E. Use of inferior spare parts in the materials

1. Why the OEE is low?

- ✓ Because after repairs, equipment breaks down quickly.

2. Why does it break down after being fixed?

- ✓ Because substitute parts are not very good.

3. Why do subpar parts get used?

- ✓ Since original equipment manufacturers or authentic parts aren't always readily available.

4. Why can't original equipment manufacturer components be found?

   - ✓ Due to inadequate purchase strategy or inadequate supplier screening.

5. What undermines procurement planning?

   - ✓ Due to inadequate technical and purchasing department coordination.

The use of inferior materials as a result of inadequate procurement coordination lowers the availability and dependability of equipment.

F. The harsh operating conditions in the environment

1. Why the low OEE?

   - ✓ Because equipment deteriorates more quickly than anticipated.

2. Why does it deteriorate more quickly?

   - ✓ Due to exposure to dust, moisture, and temperature fluctuations.

3. Why is it subjected to these circumstances?

   - ✓ Because the location and plant layout are not well organized.

4. Why isn't the arrangement optimized?

   - ✓ Because throughout the design, environmental risks were not given priority.

5. Why didn't they get priority?

   - ✓ Due to a lack of budget and vision in the early stages of planning.

The Root Cause is equipment longevity and reliable operations are decreased due to inadequate environmental management and infrastructure planning.

4.6.2 Root Cause Analysis for Cooling Water Pump Failure

From the Pareto chart developed (see Figure 4.12) we have already identified the most frequent failure in the cooling water pump, making the plant for extra costs to maintain the equipment. Now for this problem, we are going to look after RCA for its failure using the Fishbone Diagram and 5 whys.

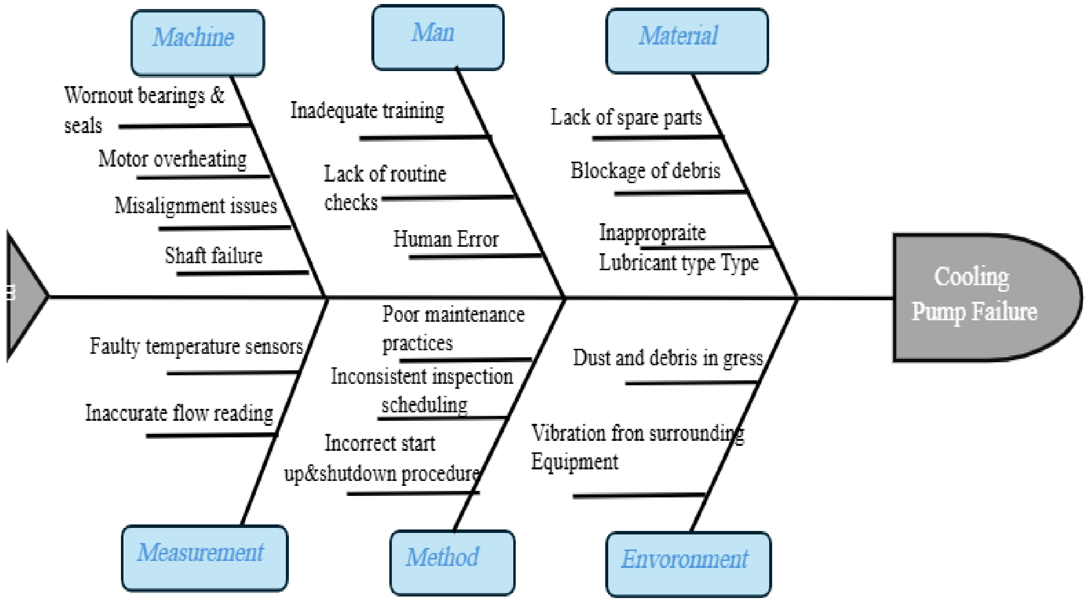

Figure 4.12 Fishbone Diagram for Cooling Pump Failure

The following descriptions of the root causes of cooling water pump failure were identified.

The cooling water pump is a critical component ensuring temperature control within the power plant equipment. Failure ceases operations, causes equipment overheating, and is attended by serious safety and economic costs. To effectively identify and remove causes of failure, the Fishbone (Ishikawa) diagram further classifies possible faults into main areas.

1. Machine (Mechanical Issues)

Mechanical failure consists of flaws in the physical equipment of the cooling pump. Flaws consist of corrosion of the moving parts like the impeller, breakdown of seals, blockage in the cooling line, or contamination with debris. For example, when particles penetrate the system by improper filtering, they clog the cooling line and lead to overheating which ultimately leads to a failure of the pump.

2. Method (Procedures and Methods)

This category includes startup, operation, and maintenance procedures for cooling pumps. Poor startup procedures, including omitting safety checks or refusing preconditions like opening the main outlet valve, are frequently due to undefined or poorly performed standard operating procedures.

3. Man (Human factor)

Human mistakes or weakened training falls under this category. Mismanagement and mechanical failure are going to occur in case the personnel are not specially trained on what to do for maintaining or operating the cooling water pump. It is caused due to understaffing, employee turnover, or lack of a proper onboarding process.

4. Material (Supplies and Components)

Material-related problems are the result of using substandard, incompatible, or degraded materials, such as faulty electrical conductors, damaged insulation, or low-quality filters. Inadequate incoming material inspection and replacement with non-original equipment manufacturer (OEM) parts can also make a significant contribution to failure.

5. Measurement (Sensors and Instrumentation)

Instrumentation errors such as faulty sensors providing erroneous information can cause the pumps to malfunction. This is essential because of less-than-optimal calibration intervals or the absence of validation procedures for the sensors, and abnormal conditions may not be easily detected or responded.

6. Environmental (External factors)

Environmental conditions are those conditions around the pump that might affect its performance, such as vibration, variations in temperature, dust, or spatial constraints. For example, positioning the pump near heavy equipment without taking into account exposure to vibration can cause mechanical loosening and failure over time.

For the identified problems we are going to find the root cause by asking for 5 whys for each pattern. The source of this analysis was from the causes of Cooling Pump Failures by Pareto chart Figure 4.10, interview with operators and maintenance personnel and real time operation observation.

A. Root causes analysis using 5 Whys of Shaft failure due to overheating and vibration:

1. Why did the shaft fail?

- ✓ Because it overheated and was subjected to excessive vibration.

2. Why did it overheat and vibrate?

- ✓ Because of improper alignment or lack of lubrication.

3. Why was there improper alignment/lack of lubrication?

- ✓ Because the planned maintenance was not executed.

4. Why wasn't maintenance executed?

- ✓ Because the team lacked trained personnel or appropriate checklists.

5. Why were the team not trained/checklists?

- ✓ Because there wasn't any formal training or maintenance planning program.

Absence of a structured maintenance planning and training program

B. Inappropriate Function Because of inadequate training

1. Why did the cooling water pump malfunction?

- ✓ Because it sustained damage while in use.

2. Why it was damaged while it was in use?

- ✓ Because the operator didn't open the main outlet valves before starting it.

3. Why did the operator neglect to open the main outlet valves?

- ✓ Because they were unsure about how to start it correctly.

4. Why were they unable to initiate it?

- ✓ Because they lacked proper training.

5. Why did their lack of training?

- ✓ Because the new operators did not have access to an established training program.

The Root Cause is inadequate training program led to improper operation, causing pump failure and damage.

C. Debris in the Coolant Line Causes Overheating

1. Why did the cooling pump malfunction?

- ✓ Since it became too hot.

2. Why did the overheating?

- ✓ Due to an inadequate flow of coolant.

3. Why did the coolant flow to be inadequate?

- ✓ Because the coolant line is blocked.

4. Why did the blockage in the coolant line?

- ✓ Because debris getting into the system.

5. Why did the material get into the system?

- ✓ Because the filter was not maintained or there was insufficient filtering.

The underlying cause is Debris got into the coolant line due to improper filtering system maintenance, which led to overheating and failure.

D. Short Circuit in Electrical Power

1. Why did the cooling pump fail?

- ✓ Because the motor suddenly stopped working.

2. Why did the motor shut off?

- ✓ Because of the electrical system short-circuited.

3. Why did the short circuit?

- ✓ Because of worn-out electrical insulation.

4. Why did the insulation wear out?

- ✓ Because it wasn't replaced and had worn out over time.

5. Why wasn't it replaced?

- ✓ Since electrical check-ups were not part of the maintenance process.

The Root Cause is a Motor failure as a result of poor maintenance planning that failed to consider worn-out wiring.

E. Failure of the Sensor

1. Why did the cooling pump malfunction?

- ✓ As it was operating with the wrong settings.

2. Why were the wrong parameters being used?
   - ✓ Due to the sensor's erroneous readings.
3. Why did the sensor provide erroneous readings?
   - ✓ Because it was broken.
4. Why was there a malfunction?
   - ✓ Because the calibration was incorrect.
5. Why was there a lack of calibration?
   - ✓ Due to the failure to adhere to calibration schedules.

The Root Cause is the pump operating in dangerous conditions as a result of sensor faults brought on by a failure to follow calibration protocols.

E. An Improperly Aligned Pump

1. Why did the cooling pump malfunction?
   - ✓ Because of excessive vibration and bearing wear.
2. Why is the bearing worn out and excessive vibration?
   - ✓ Because the motor and pump shaft were out of alignment.
3. Why was the shaft to be out of alignment?
   - ✓ Because during installation, alignment was not properly checked.
4. Why the alignment was not properly checked?
   - ✓ Because there was a lack of adherence to basic alignment procedures.
5. Why were procedures not adhered?
   - ✓ Due to lack of training or supervision during installation.

Root Cause of misalignment during installation due to lack of training or supervision caused excessive vibration and premature failure of the alignment system.

4.7 Suggested Solution

To address the extensive operation and maintenance problems experienced at Melka Wakena Hydropower Plant, a comprehensive set of systematic and harmonized improvement actions is proposed. Improvement actions are intended to enhance root cause analysis, maintenance planning, technical competence, spare parts management, interdepartmental coordination, monitoring of equipment, environmental management, and organizational culture.

Amongst areas for improvement is enhancing Root Cause Analysis (RCA) methodology. Root cause recurrence has been due to lack of systematic problem-solving processes and insufficient uptake of standard RCA tools such as the 5 Whys and Fishbone diagrams. It is therefore recommended to make RCA a compulsory practice following any significant breakdown or loss of performance. Engineers and supervisors should be trained on case studies to develop analytical skills. A computerized RC logbook should be adopted to document failures, root causes, and corresponding remedial actions in an organized format. Such RCA findings should also be argued and discussed out at a monthly performance review meeting to ensure assurance of accountability and learning within teams.

Concurrently, Total Productive Maintenance (TPM) practices also have to become fully implemented for improving equipment reliability and reducing unplanned downtime. Sporadic preventive maintenance, lack of Standard Operating Procedures (SOPs), and lack of involvement from operators have undermined TPM performance. As a corrective action, SOPs are to be formulated and adhered to strictly for key maintenance activities. Regular preventive maintenance has to be programmed with clearly laid responsibilities. In addition, an Autonomous Maintenance program must be initiated by training operators to perform routine cleaning, inspection, and lubrication on basic maintenance activities. Critical key performance indicators such as Mean Time between Failures (MTBF) and Mean Time to Repair (MTTR) also have to be monitored closely to evaluate TPM performance and inform future initiatives.

Its second concern is technical skills deficiency among technicians and operators and informality of skills transfer. To address this, skills deficiencies have to be determined by conducting continuous skills audits. Special technical training e.g., alignment procedure, balancing, and vibration analysis has to be performed to address this. Multi-skilling has to be adopted to increase labor flexibility. A mentorship model also has to be established whereby experienced technicians mentor and guide their younger counterparts for continuous skills acquisition.

In terms of spare parts component lead times and the quality of non-OEM or substandard parts have affected equipment performance. For this, a list of necessary spare parts should be created and minimum stock levels maintained to meet emergency demands. Procurement monitoring with lead-time reminders should be introduced to improve planning and response. A vendor rating system also needs to be established to prioritize vendors with a history of delivering quality and reliable parts. The purchasing unit needs to participate in maintenance planning meetings to facilitate timely and accurate fulfillment of needs.

Coordination also must be bolstered noticeably among maintenance, budget, and procurement departments. Misalignment of maintenance needs with approval for purchasing and delay in releasing the budget often leads to unavailability of key tool and resource needs. To rectify this, coordination meetings need to be arranged on a monthly cycle involving technical, finance, and purchasing departments' representatives. A maintenance budget calendar must be established to ensure better predictability and planning. Departmental heads should also be enabled to make requests for tools and resources directly with rationales supported by equipment efficiency and urgency. Procurement must become need-oriented and prioritized on evidence-based data.

Power plant monitoring systems and instrumentation also require upgrading. There also exist several uncalibrated sensors and partially defective sensors and no systematic early warning system. All major sensors such as vibrations and temperatures can be replaced or recalibrated from time to time. SCADA or CMMS is recommended to allow for on-line condition monitoring of the equipment. Fault alarm and diagnosis data must also be logged and utilized for helping predictive maintenance activities. Training for condition monitoring and alarm response for technicians and operators also must also be performed.

Equipment reliability also has an impact from structure and environmental factors. Lack of proper protection from dust, vibration, and heat will result in wear and hasten failure. Protective coverings must be installed on exposed apparatus, and sealed enclosures installed on control and electrical panels to prevent moisture and dirt from entering. Equipment exposed to harsh environments must either be moved elsewhere or provided with a proper covering to limit the exposure.

Finally, for sustainability of these improvements, a culture of continuous improvement needs to be embedded. Improvement actions are disjointed and lack consistency in strategy. To set this right, a Kaizen suggestion scheme needs to be implemented, where employees need to be encouraged to make suggestions for efficiency improvements and problem-solving. TPM performance dashboards need to be shared and communicated among all employees so that they can view them and learn from them, making it transparent and accountable. An award system needs to be implemented to recognize teams or individuals affecting considerable downtime or improving key performance measures. TPM and RCA learning sessions need to be conducted from time to time so that there is a shared culture of problem-solving and shared accountability of performances.

In brief, these interrelated recommendations are to be implemented wholesale to improve reliability, maintainability, and general plant performance for the Melka Wakena Hydroelectric Power Plant. By encouraging systematic problem-solving, developing competence, enhancing coordination, and fostering an improvement culture, the plant can achieve long-term gains in performance and process excellence.

Based on the suggested solutions we developed the following model that shows how OEE of the power plant generators will be enhanced.

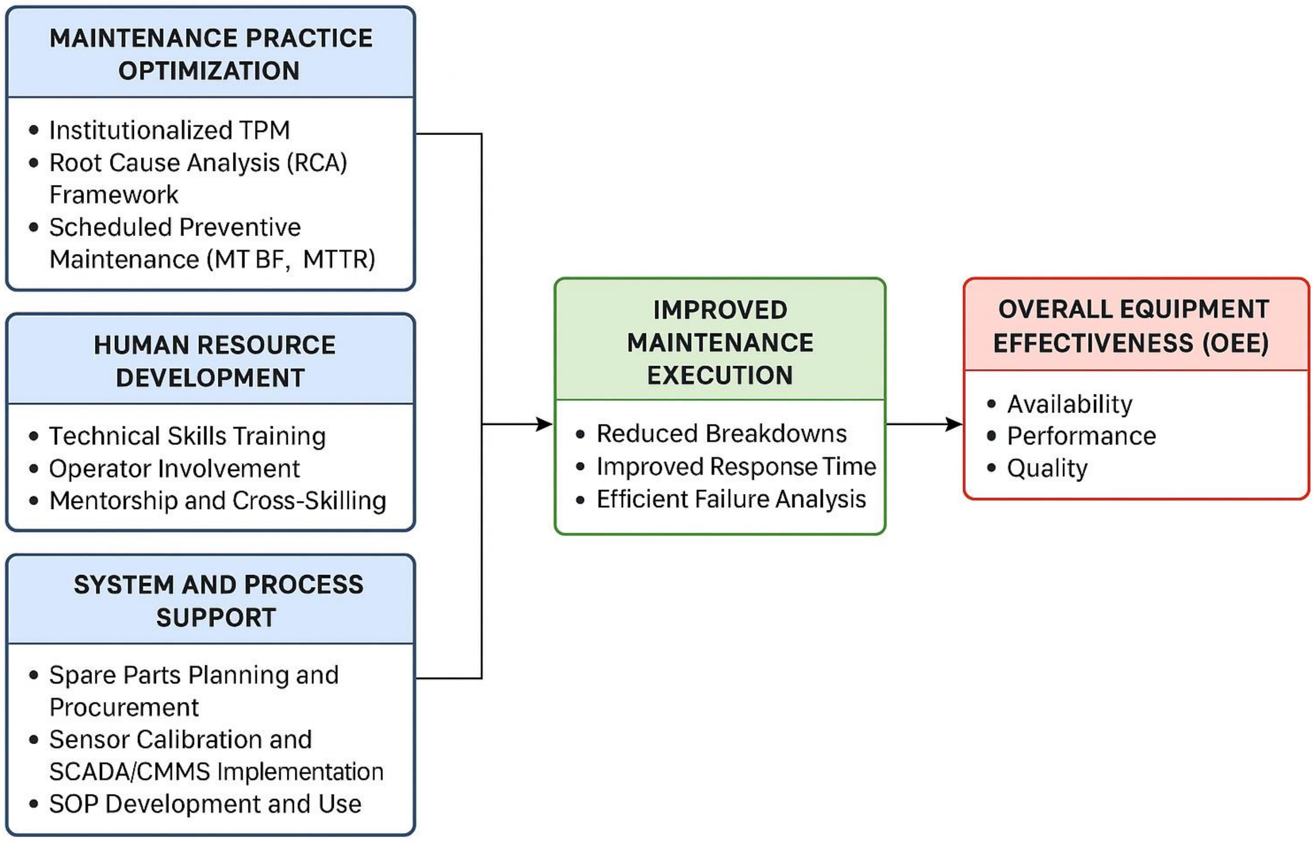

Figure 4.13 Conceptual solution model of the OEE enhancement of the power plant

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study explored the underlying reasons for the poor Overall Equipment Effectiveness (OEE) of the Melka Wakena Hydroelectric Power Plant and explained how Total Productive Maintenance (TPM) and Root Cause Analysis (RCA) can help enhance efficiency. The results obtained from the calculation of OEE, the Six Big Losses analysis, classification using the Fishbone Diagram, the application of the 5 Whys technique and verification using questionnaires give a clear notion of performance bottlenecks and the ways to improve. The investigation established that the significant causes of low OEE include unplanned downtime, poor operational procedures, and lack of training, poor measuring systems, poor-quality spare parts, and poor environmental conditions. The majorities of these causes are the result of poor implementation of TPM pillars of preventive maintenance, autonomous maintenance, and focused improvement. RCA tools like Fishbone Diagrams and the 5 Whys technique revealed that root causes are often systemic rather than operational, highlighting the importance of cultural and structural changes. While TPM and RCA principles are to some extent self-evident, their complete incorporation into organizational routines is missing. Maintenance routines are still largely reactive, training activities lack systematic structuring, SOPs are implemented irregularly, and failure data is not adequately leveraged to guide corrective actions. A concerted and systematic effort to adopt TPM and RCA as frameworks for continuous improvement is therefore instrumental for the facility to increase its OEE and more closely approximate international performance standards.

5.2 Recommendations

From the study findings and the analysis, the following solutions are suggested to improve the OEE and operational reliability of Melka Wakena Hydroelectric Power Plant::

1. Apply Total Productive Maintenance as a strategy in the power plant

- Establish TPM pillars and respective responsibilities.
- There have to be cross-training programs implemented in such a way as to make the operators more flexible and foster team building.

- Embed autonomous maintenance, preventive maintenance, and training into regular working practices.

2. Standard Operating Procedures

- List and execute SOPs for shut-down and start-up, equipment inspection, and emergency operation.
- Revise and update the procedure periodically and train the operators.

3. Formal Training Plan Formulation

- Create a competence matrix and provide targeted training to offset deficiency of skills.

4. Strengthen RCA Implementation

- Make the application of 5 Whys and Fishbone Diagrams compulsory in all root cause analyses.
- Continue to keep an RCA report of repeated failure modes and actions.

5. Improve Spare Parts and Procurement Management

- Make a conscious effort to actively screen the suppliers and normalize OEM-quality part purchasing.
- Manage inventory tracking and set reorder points to avoid purchasing crises.

6. Instrumentation and Monitoring Upgrade

- Perform routine sensor calibration and implement more advanced SCADA systems to improve data accuracy.

7. Develop ongoing Improvement

- Engage employees on problem-solving teams. Reward and recognize efforts that lead to measurable performance improvement.

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APPENDIX I

Questionnaire

Section 1: Questions on TPM

1. We perform preventive maintenance regularly

Strongly Disagree Disagree Somewhat Disagree Neutral Somewhat Agree

Agree Strongly Agree

2. Operators are trained to maintain equipment

Strongly Disagree Disagree Somewhat Disagree Neutral Somewhat Agree

Agree Strongly Agree

3. Autonomous Maintenance is implemented

Strongly Disagree Disagree Somewhat Disagree Neutral Somewhat Agree

Agree Strongly Agree

Section 2: Questions on RCA

4. We conduct RCA after equipment breakdown

Strongly Disagree Disagree Somewhat Disagree Neutral Somewhat Agree

Agree Strongly Agree

5. Corrective Measures are taken from RCA

Strongly Disagree Disagree Somewhat Disagree Neutral Somewhat Agree

Agree Strongly Agree

6. RCA is involved in the plant

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree
☐	☐	☐	☐	☐

Agree	Strongly Agree
☐	☐