Addis Ababa University

Addis Ababa Institute of Technology (AAIT)

School of Mechanical & Industrial Engineering (SMIE)
(Industrial Engineering Stream)

MSC Research on:

Improving Operational Performance by prioritizing Lean Maintenance Tools: A Case Study of Reppie Waste-to-Energy Power Generation Plant

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DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "Improving Operational Performance by prioritizing Lean Maintenance tools in Reppie waste–to-energy power plant" is my original work, has not been presented for a degree in this or any other university, and all the resource materials used for this thesis had been accordingly acknowledged.

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ACKHONOLODGEMENT

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ABSTRACT

The main purpose of this research is to improve operational performance in waste-to-energy (WTE) plant facility by prioritizing lean maintenance tools. Waste-to-energy power plants are complicated systems that need several maintenance strategies to be available and efficient in all of their functionalities. The Operational performance; availability, efficiency, quality maintenance and maintenance costs of the WTE plants are significantly impacted by maintenance performance. The shortcomings of WTE facilities' lifetime maintenance could lead to higher production costs, a decrease in ability to compete, increased downtime, and a higher mean-time-failure rate. This study aims to improve operational performance by applying the selected Lean Maintenance Tools (LMT) framework in the case company. Data relevant to the research was collected among employees in different positions within the organization to evaluate the potential for operational performance improvement using designed questionnaire, informal interview, direct observations, and company records. The reliability and validity of the survey findings were confirmed through a triangulation approach, incorporating various data collection methods. In order to analyze the collected data from primary and secondary sources, the researcher has used descriptive analysis method such as Analytic Hierarchy Process (AHP), SPSS software and Pareto diagram.

The selection of lean maintenance tools can help identify and address potential waste areas in equipment failures by prioritizing lean tools in maintenance strategies. AHP tool prioritization of LMT and operational dimension has been calculated. The most prioritized lean maintenance tool on the survey is TPM while the least emphasized tool is Kanban system. The findings of this study supports the promotion of sustainable operation, waste management practices, reduced maintenance cost and increased renewable energy production efficiency. The researcher then selected the top five LMT above listed that can address significant impact in affecting operational performance and finally proposed a new implementation framework including operational procedure and action plan that are going to be practiced.

Keywords: RWtE, Lean maintenance tools, AHP, Operational performance, MSW

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ACRONYMS

WTE- waste-to-Energy

RWtE- Reppie waste-to-energy

OP- operational performance

APH- analytical hierarchy process

SPSS- statistical package for the social science

TPM- Total productive maintenance

OEE- over all equipment effectiveness

ROI-Return on Investment

RCA- root cause analysis

LMT- Lean maintenance tool

VSM- Value stream mapping

RCM- Reliability Centered maintenance

HAZOP- Hazard and Operative analysis

FTA- Fault tree analysis

PM- Planned Maintenance

FMEA-Failure Mod & Effect Analysis

QCC- Quality Control Circle

CHAPTER ONE

1. Introduction and Research Justification

1.1 Introduction

Today's enterprises need to be able to produce high-quality products with flexibility in their operations [2]. The aforementioned demands underscore the necessity of maintaining high standards of entire system reliability of personnel, machinery, equipment, material handling systems, other value-adding systems, and managerial operations across the production system [3]. Inadequate plant maintenance is frequently associated with low productivity, high downtime, and low machine performance. These factors might result in fewer profitability, lost market opportunities, higher costs, and decreased output levels. Due to these losses, enterprises all around the world are now more inclined to investigate and use proactive maintenance techniques than following conventional reactive firefighting techniques [4].

Now a days, the rapid increment of municipal Solid Waste (MSW) has harmed human health and the global environment. The rapid growth is, due to the rapid change or increase of population, urbanization, and energy or resource consumption [5]. By 2050, the total amount of MSW in all over the world will estimated to become 3.4 billion tons[5]. Therefore, the management of all these huge amount of waste is a challenge for our and future generation. So that, the only viable way to minimize a total mass waste is by recycling or reusing it. For those recycling is not suitable, municipal solid waste-to-energy power plants have emerged as a crucial solution for sustainable waste management and renewable energy generation.

Effective maintenance procedures are necessary to guarantee the seamless functioning and peak efficiency of waste-to-energy systems. Reactive, traditional maintenance methods that fix equipment after it breaks down can lead to more downtime, more expensive maintenance cost, and less operational effectiveness or availability. Applying lean maintenance techniques has emerged as a viable strategy to address these issues and improve industrial facilities' operational performance, particularly waste-to-energy power plants.

Lean thinking, moreover, has been proven to lead to higher levels of production efficiency in many industries across many regions of the planet [6].

However, it is impossible to achieve lean without equipment that is as reliable and available as possible because these factors directly affect the final product's quality, production volume, price, and delivery. Then, in order to get the production system to operate as needed, organizations need to determine the best maintenance plan. Furthermore, although lean manufacturing is a widely recognized idea among researchers and industrialists, lean maintenance is less well-known and has not received much attention from researchers.

Lean maintenance focuses on eliminating waste, optimizing resource utilization, and implementing proactive maintenance strategies. By adopting lean maintenance principles and tools, waste-to-energy power plants can improve maintenance processes, minimize downtime, reduce costs, and increase equipment reliability. The application of lean maintenance tools, such as 5S, TPM (Total Productive Maintenance), VSM (value Stream Mapping), visual management, standardized work, and continuous improvement methodologies (kaizen), can lead to streamlined maintenance works. Lean maintenance is a system that encompasses different maintenance principles and existing lean techniques and aims to eliminate the various wastes identified in maintenance processes [7]. Therefore, the aim of this research is to increase the operational performance of the case company by prioritizing lean maintenance tools by using the analysis methodology tools called AHP.

In business environment, in order to reach high performance and productivity of an organization, it is essential to develop and implement new strategies and react quickly to remain competitive. Attaining reliability and availability of equipment's is very important for industries facing high maintenance related problems.

Background and Justification of the study:

There are thousands of waste-to-energy plants found around the world, and most of them employ a similar process to that of Reppie Waste to energy power plant. Reppie WtE power plant started its operation in early October, 2019 G.C as one of the first African WtE power generation plant located in Addis Ababa, under the owned state of Ethiopian Electric power. The plant is designed to convert municipal waste into electricity, contributing to the people's effort to address both waste management challenges and energy demand in the country.

However, suboptimal operational performance, frequent breakdowns, and extended downtime can hinder its efficiency. By prioritizing lean maintenance tools and development of new framework can solve the problem, this study aims to optimize maintenance processes, reduce downtime, and improve overall operational efficiency of Reppie waste-to-energy power plant. The findings can contribute to increase energy generation, reduced maintenance waste, increased waste intake volume, reduced fuel consumption for ignition and enhanced sustainability.

Inefficient maintenance practices in Reppie WTE power plant results in high maintenance costs, including reactive repairs, unplanned shutdown. Selecting and prioritizing lean maintenance tools can help identify and eliminate waste in maintenance processes, leading to cost reduction and increased machine availability. This study will explore ways to optimize resource utilization, increase machine uptime, minimize maintenance expenses, improve performance and improve the cost-effectiveness of Reppie waste-to-energy power plant operation by minimizing of waste in maintenance process.

The selection of lean maintenance tools can help identify and address potential waste areas in equipment failures through prioritizing lean tools in maintenance strategies. By improving equipment reliability, could reduce breakdowns, extend equipment lifespan, and improve the overall reliability and availability of the plant assets.

This organization contribute to sustainable waste management practices and renewable energy generation in Addis Ababa. By improving operational performance through lean maintenance, and can further improve its' sustainability credential. The findings of this study will support the promotion of sustainable operation, waste management practices, reduced maintenance cost and increased renewable energy production efficiency.

In recent years**,** although the concept of lean maintenance is well-established in various industries, but the selection of the appropriate tools in the context of waste-to-energy power plants is relatively limited. This study will contribute to the body of knowledge by prioritizing effectiveness and applicability of lean maintenance tools in the case company. The research outcomes can serve as a reference for other similar facilities, researchers, and industry professionals interested in eliminating wastes in maintenance practices to achieve improved operational performance.

The findings of this study benefits multiple stakeholders such as: the plants' operational staffs, operators and maintenance personnel can improve their operational efficiencies, reduce costs, and enhance their environmental performance. Local communities will benefit from increased energy generation, reduced environmental impacts, and improved waste management practices.

Additionally, policymakers and regulatory bodies can use the study's insights to develop guidelines and regulations that promote sustainable waste management and efficient operation of waste-to-energy power plants.

Therefore, this study's justification lies in the potential to improve operational performance, reduce costs, improve equipment reliability, promote quality maintenance, contribute to knowledge advancement, and provide benefits to various stakeholders involved in Reppie MSW power plant operations.

1.2 Problem statement

Due to the city's rapid growth and per capita income increase, a considerable volume of solid garbage has been generated. Similarly the energy needs of Ethiopia are expanding, and the state must have access to a diverse range of energy sources, including new technologies like WTE, that alleviate dependence on factors outside of its control. One of the most significant sources of urban pollution is municipal solid waste (MSW), which is produced in significant amounts in the fastest-developing cities like Addis Ababa. The government of Ethiopia built the Reppie Waste to Energy power plant, in response to the rapid growth of urbanization and pollution in order to create a clean, healthy, and best city[8]. However, Reppie WTE power generation facility faces operational challenges that hinder its efficiency and effectiveness. One significant area of concern is, the problem of maintenance practices performed in this power plant. Inefficient, wasteful and suboptimal maintenance processes can lead to increased downtime, equipment breakdowns, higher costs, and overall reduced operational performance.

In RWtE, 2014 E.C report shows that the annual energy generation downtime is 80% that is due to equipment failure. This shows that the current maintenance practices in the company is negatively impacting production schedules and overall productivity. This indicate that, there is a need to improve the current maintenance waste to minimize downtime while ensuring equipment reliability and uptime. Additionally, in the case company, the observation shows that, resources, such as: manpower, materials, and tools are being underutilized or misallocated with in maintenance process. Therefore, an improvement strategy is required to efficiently identify the source of problem areas and utilize resources, thereby improving overall operational performance. The company’s maintenance survey shows that there is no performed scheduled overhaul maintenance for the last five years; due this, Frequent breakdowns and unplanned equipment failures lead to unscheduled maintenance activities, disrupting production and causing performance losses (indicator currently the turbine is working with a generating capacity of 32% due to shortage of scheduled overhaul or planned maintenance). So that, prioritizing and selecting Lean maintenance tools will aims to reduce these occurrences through elimination or minimization of wastes in maintenance practices. Improper selecting of maintenance activities can lead to disruptions in production schedules, causing maintenance delays and inefficient performance.

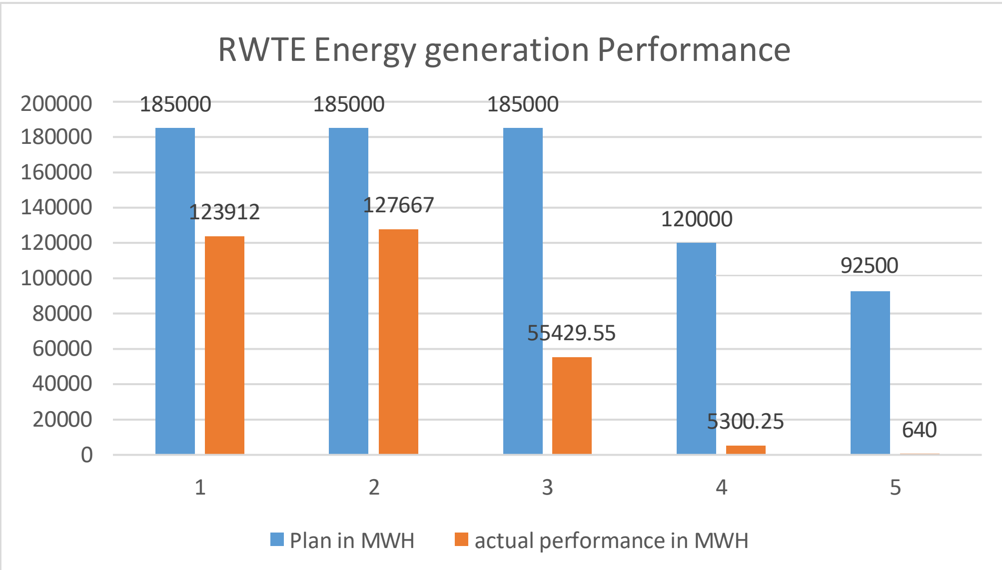

Figure 1.1**:** RWTE five years energy generation performance

To mitigate the above problems in RWtE power plant implementing proper maintenance system is required by prioritizing Lean Maintenance tools to align with production needs, high quality, minimized lead time, ensuring smoother operation, and to give sufficient training and also skill development for maintenance personnel can lead to optimal execution of tasks.

Despite the recognized importance of maintenance in the case company, there is a lack of research and practical guidance on how to effectively use the proper lean maintenance tools in this specific context. Lean maintenance, rooted in the principles of Lean Management, offers a systematic approach for eliminating waste in maintenance, improving efficiency, and enhancing overall operational performance. However, there is a need to explore how these lean maintenance tools can be adapted and applied to address the unique challenges and complexities of Reppie WTE power generation plant [9][10].

Therefore, the problem addressed by this thesis is the lack of a comprehensive proper selected lean tools for improving operational performance. The existing maintenance practices in the company often fall short in terms of efficiency, reliability, availability and maintenance cost-effectiveness.

1.3 Research Question

Based on the research problems, the following are main research questions:

- What are the key Lean maintenance tools (LMT) that can be prioritized to enhance operational performance at Reppie Waste-to-Energy power generation plant?
- How do the prioritized Lean maintenance tools impact equipment availability and maintenance costs at the Reppie plant?
- What challenges does the reppie Waste-to-Energy power generation plant face in implementing Lean Maintenance tools, and how can these challenges be addressed?
- What measurable improvements in operational performance can be observed after implementing the recommended Lean Maintenance Tools at the Reppie plant?

1.4 Objective of the study

1.4.1 General Objective

The general objective was to improve operational performance at the Reppie Waste-to-Energy Power Generation plant by prioritizing and implementing Lean Maintenance tools.

1.4.2 Specific objective

- To identify and prioritize the most effective lean maintenance tools (LMT) applicable to the Reppie Waste-to- Energy Power Generation Plant.
- To evaluate the impact of prioritized Lean Maintenance Tools on equipment availability, efficiency, and maintenance costs at the plants.
- To analyze the challenges associated with the implementation of Lean Maintenance Tools and propose strategies to overcome these challenges.
- To assess the operational performance improvements resulting from the implementation of Lean Maintenance tools at RWtE power generation plant.
- To develop a comprehensive improvement strategy that outlines the steps for effectively implementing Lean Maintenance Tools to enhance operational performance at Reppie Waste-to-energy plant.

1.5 Scope and limitation of the study

The scope of the research primarily limited to operational performance improvement of the Reppie waste-to-Energy power generation plant by analyzing the existing lean maintenance practices and prioritizing the tools that significantly affects operational performance starting from waste reception to the final product or energy dispatch. It does not include all lean maintenance tools rather limited to selected lean maintenance tools only. Moreover, it does not consider lean manufacturing tools. In addition, the scope does not include the investigation of the result from the application of the developed framework due to time constraints.

1.6 Significance of the study

The significance of the study lies in its potential to contribute to most well-known and important programs, to the optimization and efficiency of the Reppie waste-to-energy power generation plant by addressing current challenges. Its function extends beyond machine uptime to take into account every problem with equipment performance by incorporating both technical and human factors. As a result, the researcher thinks that this study will continue to play a vital role for the company's that still views maintenance as a cost-center activity and lack of operational performance improvement especially in WTE plant. The proposed framework can be used for Reppie Waste-to-Energy plant in achieving organizational efficiency and excellence, increased employee engagement, better customer satisfaction and sustainable competitive advantage. And also used for various manufacturing industries to increase their operational performance. Additionally, it could serve as a starting point for future researchers who wish to conduct additional research.

1.7 Benefit of the research

- The research can show improved operational performance through prioritizing lean maintenance tools.
- The research can help and encourage MSW to energy power plants to use the appropriate lean maintenance tools which best suits to improve operational performance.
- The result can show the gap of the case company and show as a measuring point for improvement.

1.8 Organization of the research

The first chapter show a brief overview of the research objectives, the problems and issues addressed in the research and motivation for the research. The second chapter overviews a literature review of the research work performed in the areas for maintenance optimization, lean maintenance program and operational performance in manufacturing industries. The third chapter deals with the research methodology and overviews of the case company's operational activities. The fourth chapter presents with the validation, show the result and discussion parts. Fifth chapter provide the development of proposed framework and application action plan. Finally the six chapter provide conclusions and recommendations.

CHAPTER TWO

2. Literature Review

2.1 Introduction to lean maintenance

The phrase "lean maintenance" was first used in the last decade of 20^{th} century. "A proactive maintenance operation employing planned and scheduled maintenance activities. Lean maintenance reduces input usage to produce a desired result.

Integrating lean concepts into maintenance, repair, and overhaul (MRO) processes is known as lean maintenance. By optimizing maintenance overhead and support tasks, it could lower unplanned downtime. For the purpose of implementation, the lean principles are represented by the lean tools[11][12].

2.1.1 Lean Philosophy

The roots of the Lean philosophy trace back to the early 20th century, primarily emerging from the automotive industry. Since the 1950s, this philosophy has undergone substantial development, with notable successes, notably demonstrated by the renowned Toyota Production System (TPS). The Lean philosophy, famous for its effectiveness, has found extensive application not only in manufacturing sectors but also across diverse industries. Its primary objective is to minimize waste and enhance overall productivity[13].The primary objective of lean is to mitigate waste, increase value-added activities (goods and services), and provide value for customers (customer value) [14].

The Lean philosophy, commonly known as Lean, encompasses a set of established tools and techniques designed to eliminate operational waste [15]. Its central aim is to improve the value of end products or services by aligning with customer needs. Within the framework of Lean philosophy, activities are categorized into two distinct types: value-added and non-value-added. Value-added activities directly contribute to the creation of value in the final products or services, representing processes for which customers are willing to pay.

Conversely, non-value-added activities do not directly contribute to the value creation process. While certain non-value-added activities, like administration, are necessary, others are considered "waste" and are targeted for elimination. The fundamental principle of Lean philosophy revolves around waste elimination and continuous improvement. As such, the philosophy prioritizes the removal of resources and efforts expended on non-value-added activities to enhance efficiency and drive continuous improvement[16].

2.1.2 Lean Operations

Initially, Lean Manufacturing techniques were primarily oriented towards enhancing productivity rather than focusing on quality. However, the pursuit of improved productivity inadvertently reveals inefficiencies and quality issues within operations. Consequently, the emphasis broadens to not only target waste but also address factors that compromise quality and pose management challenges [17].

In alignment with [18], Lean Operations involves the reduction and elimination of activities that do not contribute value. As a natural outcome, enhancements in performance manifest across dimensions such as quality, costs, speed, and the reliability of delivery [19]. Additionally, Lean Operations extends to maintaining order and cleanliness in the physical workplace, forming a fundamental aspect of the 5S philosophy. The 5S philosophy, foundational to lean manufacturing, offers principles that effectively organize the workplace, ensuring cleanliness and orderliness [10]. The implementation of 5S results in a more efficient, clean, orderly, and safe work environment, concurrently reducing unproductive times, movements, and cost.

2.2 Maintenance and Lean Maintenance

Maintenance encompasses a series of activities conducted to preserve the machinery's capacity to produce products at the required quantity and quality levels [20]. In today's competitive landscape, companies should perceive Maintenance not just as a necessity but as a potential avenue for cost savings and gaining a competitive edge. The enhancement of maintenance activities is pivotal in attaining production objectives and, consequently, the overall goals of the company, as illustrated in Figure 2 [10].

Inadequate maintenance adversely impacts consumer confidence. Frequent equipment failures result in unplanned downtime, affecting timely deliveries to customers. Persistent delays can tarnish the company's reputation, leading to significant economic repercussions. Therefore, it is imperative to view maintenance not merely as a cost but as a profit center.

According to [21], the primary goal of maintenance is achieving "total asset life cycle optimization" in a manner that is cost-effective and complies with environmental and safety regulations. Therefore, maintenance management needs to be synchronized with business activities at strategic, tactical, and operational levels. [22] Defines maintenance management as the set of activities aimed at achieving efficiency, effectiveness, and cost-effectiveness in maintenance, ultimately contributing to the company's profitability and competitiveness.

Based on this, there are two main types of maintenance strategies:

Preventive maintenance (PM)

PM was begun in the 1959s. Its aim is to prevent the existence of break down equipment's through regular basis maintenance activities to lengthen the equipment life.

According to European Standard PM was defined as maintenance work done on an object at predefined intervals or in accordance with specified criteria with the goal of lowering the likelihood of failure or deteriorating its functioning [23].

Breakdown maintenance

Run to failure maintenance is a kind that was first implemented in the 1950s.The fundamental idea is to let machinery run until it breaks and then fix or replace broken equipment based on evident issues arise.

The implementation of lean methodologies, in this context, should extend beyond manufacturing efficiency to encompass lean maintenance practices, ensuring comprehensive success [11]. Lean Maintenance involves applying Lean principles to maintenance processes with the goal of reducing downtime. Utilizing tools such as Value Stream Mapping (VSM), 5S, Total Productive Maintenance (TPM), Kaizen, among others, it aims to streamline maintenance activities and enhance overall operational efficiency [11].

The goal of Lean Maintenance is to minimize waste by eliminating activities that do not contribute value and are not perceived as valuable by customers—such as waiting times, unnecessary movements, excessive maintenance, redundant resource allocation, and rework [11]. Additionally, reducing waste in maintenance leads to improved organization in spare parts inventory, a decrease in Mean Time to Repair (MTTR), and the standardization of maintenance procedures.

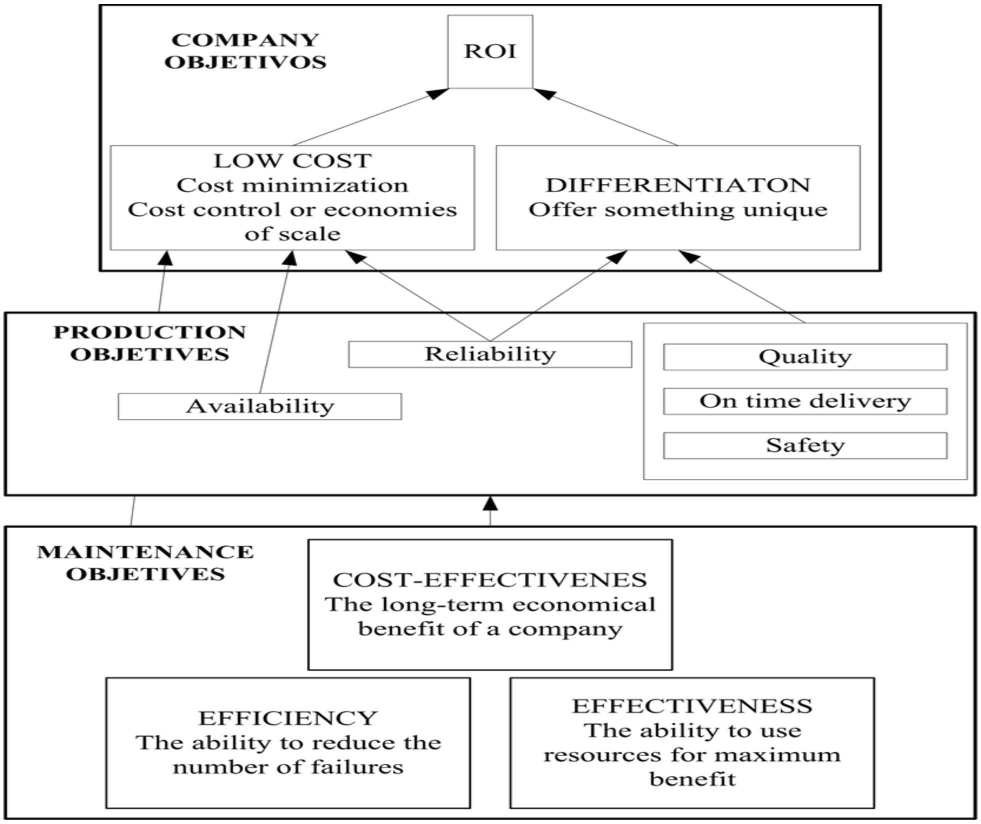

Figure 2:1 Maintenance and its objectives aligned to the organizational objective. Source: Developed from [15]

In the category of maintenance processes, it is also feasible to identify the seven primary types of waste, as some authors define the following:

Inadequate Maintenance Practices:

- Description: Implementation of excessive preventive maintenance at non-optimal frequencies [11].
- Significance: Considered detrimental as it contributes to various other forms of waste, as noted by [29].

Resource-Related Delays:

- Description: Delays in maintenance services due to factors such as permit acquisition, waiting for tools, documentation, spare parts, specialized service, etc. [11].
- Significance: Results in inefficient use of time and resources, contributing to delays in maintenance activities.

Centralized Maintenance Challenges:

Description: Maintenance stores located at a distance from workstations, leading to difficulties in accessing spare parts, unavailability of work orders, and excess transportation [11].

Significance: Hinders operational efficiency, leading to unnecessary transportation-related waste.

Substandard Maintenance Practices:

Description: Poor maintenance practices serving as a source of rework, impacting maintenance costs and the quality of service [11]

Significance: Increases costs and reduces service quality, potentially caused by unnecessary inspections or suboptimal maintenance practices [24]

2.3 Lean manufacturing VS Lean maintenance

Although Lean manufacturing tools and principles have been incorporated into Lean maintenance, the two processes: production and maintenance never can be equal in the Lean maintenance strategy [25].

2.3.1 Lean Manufacturing

Lean Manufacturing starts with the reduction of costs and elimination of waste through the Quality assurance techniques play a crucial role in the optimization of product value[26]. As indicated by [27], Lean Manufacturing further draw attention to the maximization of product value through the elimination of hidden wastes embedded in policies, procedures, processes, product design, and operations. These wastes, consume resources without contributing value to the final product. To achieve Lean status, a company must adopt an integrated approach spanning from suppliers to clients. The foundational principles of Lean Manufacturing encompass Total Productive Maintenance (TPM), 5s, Worksite Organization, Setup Time Reduction, Cellular Manufacturing, and Kaizen or Continuous Improvement and others.

Lean manufacturing reorganizes a manufacturing firm in to cells and value streams to improve the quality, flexibility, and customer response time of their manufacturing process. Lean manufacturing is very powerful in increasing operational performance on quality[28].

2.3.2 Lean Maintenance:

Lean maintenance, on the other hand, applies lean principles specifically to maintenance operations within a manufacturing or industrial environment. It focuses on optimizing maintenance processes to minimize downtime, reduce costs, and enhance asset reliability and availability. Lean maintenance involves strategies such as predictive maintenance, preventive maintenance, Total Productive Maintenance (TPM), and Reliability-Centered Maintenance (RCM). The goal of lean maintenance is to ensure that equipment and machinery operate efficiently, with minimal unplanned downtime and resource wastage.

Both lean manufacturing and lean maintenance share the overarching goal of improving efficiency and reducing waste, they target different aspects of operations within an organization. Lean manufacturing concentrates on optimizing production processes, while lean maintenance focuses on enhancing the reliability and effectiveness of maintenance activities to support those processes. However, the two can work synergistically within an organization to create a leaner, more efficient overall operation.

2.4 Lean Maintenance Tools and Techniques

The concept of lean applies to many aspects of manufacturing, operations, maintenance, and any process in general. As explained in the previous section Lean aims to eliminate the unnecessary portions of an activities.

Lean maintenance approaches finds its origins in Total Productive Maintenance (TPM) a strategy that maximizes effectiveness through overall organizational involvement. The components of lean maintenance tools include a range of approaches and procedures meant to maximize the efficiency of maintenance and repair procedures. Among the crucial components are: [29]

5s principles: The goal is to optimize efficiency and accelerate task execution by eliminating unnecessary movements through appropriate tool and equipment placement, along with cleanliness and organization. Emphasis is placed on efficiently organizing the workspace and implementing standardized work procedures [29]

TPM: The objective is to enhance equipment effectiveness through strategic maintenance and optimization techniques. TPM mandates the involvement of all staff in productive tasks, assigning them responsibility for autonomously maintaining the machines they operate. It serves as a fundamental methodology in all Lean Manufacturing initiatives, as the improvement of processes and production is contingent on the sustainable performance of equipment and machinery [29]

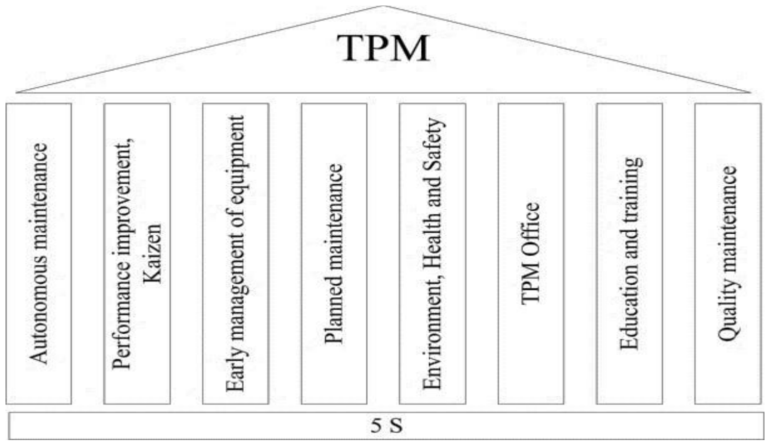

Figure 2.2 Pillars of the TPM. Source [17].

TPM can identify six categories of losses, losses by .1 failures; 2. Adjustment or configuration;

3. Minor stops and empty runs; 4. Reduced speed; 5. Reworks, defects; 6. Starts. The losses 1 and 2 affect the **availability**, the 3 and 4 to the **Performance**, the 5 and 6 to the **quality**.

KAIZEN: It refers to the search for continuous improvement, based on the fact that a small increment is more effective than one times big value improvement.

Kaizen primarily employs to eliminate wastes or Muda by japan word by using tools such as 5S, Brainstorming, Continuous Flow, Kanban, Verification Sheet, 5 Whys, Pareto, VSM, and Gantt chart. These tools are geared towards making gradual, incremental enhancements, providing essential support to sustain other Lean improvement endeavors like TPM or JIT. The ultimate goal of Kaizen is to attain and sustain zero losses related to minor stops, adjustments, defects, and unavoidable downtime. Successful implementation relies on effective leadership, thorough planning, and robust performance measurement, particularly crucial for the teams responsible for designing and executing the improvements [29].

Single-Minute Exchange of Die (SMED): Aims to reduce setup times for quicker repairs and maintenance tasks, and also used for enhancing efficiency.

VSM (Value Steam Mapping): used to analyze, design and manage the flow of material and information required to bring a product to a customer [30].

Kanban System: Utilizes visual cues to manage spare parts inventory, improving workflow and reducing downtime

RCM (Reliability-Centered Maintenance): RCM is a process used to determine the maintenance requirements of physical equipment in their present operating condition, it identifies the different ways a work center, equipment, or process could fail. RCM focuses on optimizing maintenance effectiveness.

Predictive Maintenance (PDM): Predictive maintenance techniques control the maintenance using the weight data and analytics to control equipment failures in advance and perform maintenance tasks before break down issues occur. By monitoring equipment health indicators, such as vibration, temperature, or lubricant condition, maintenance teams can optimize maintenance schedules and minimize downtime [31].

Root Cause Analysis (RCA): Determines the fundamental problems that lead to malfunctions, it identifies the different ways a piece, a process or equipment did fail and allowing for focused fixes and preventative measures.

Overall Equipment Effectiveness (OEE): serves as a metric to evaluate the effectiveness of equipment by considering its availability, performance, and quality, expressed as a percentage [32]. TPM primarily relies on OEE as a key performance indicator. The calculation of OEE takes into account significant production losses, including breakdowns, minor stoppages, changes, and reduced speed, defects, and adjustment waste [11].These losses are categorized into three key dimensions: availability, performance rate, and output quality rate. OEE is derived from the combination of these three performance measurements.

- Availability= (Loading time- Downtime)/Loading time

The loading time is the time that the machine is supported to be scheduled
Downtime is a period during which equipment or a machine is not functional.

- Performance efficiency= (processed amount*Actual cycle time)/ operating time

Process amount is the quality of product which is used for production of the output.
Actual cycle time is the actual time it takes for one machine to complete all of its operations.
Operating time is a period during which a system is working in a manner acceptable to its operator.

- Quality rate= (processed amount-Defect amount)/Processed amount

Defect amount is the quantity of a product which is not used for production.

The components above contribute to the determination of indicator of OEE that globally expresses the production line effectiveness, and is defined as:

OEE= Availability*Productivity efficiency*Quality rate= A*PE*QR

Six sigma: Six Sigma aids in defect identification and elimination, process improvement, and overall performance optimization.

No	Authors	Lean maintenance tools/techniques	Titles
1	Davies, R.M. Greenough. C. 2003	Standards, Poka-Yoke, RCA, process activity mapping, TPM, inventory management, story boarding, visual management, self-audits, continuous improvement	Testing performance measures within maintenance
2	R .Smith, B. Hawkins, 2004	5S, 7 Deadly Wastes, standardized work, VSM, Kanban, Jidoka, Poka-Yoke, JIT	Lean maintenance: reduce costs, improve quality, and increase market share
3	R. Smith, , 2004	Proactive maintenance, planned and scheduled maintenance, TPM, RCM, empowered action teams, 5S, Kaizen, autonomous maintenance, multi-skilled maintenance technician, Work order system, CMMS, Enterprise asset management (EAM), Distributed, just-in-time, Maintenance and reliability engineering group	R.Smith, , What is Lean maintenance
4	A. Zwas,2006	Jidoka, Just-in-time, Heijunka, Kaizen	Lean Manufacturing Techniques in Bus and Rail Maintenance
5	C. Davies, R.M. Greenough. 2010	5S, TPM, OEE, Standards, Mapping, Inventory Management, Visual Management, RCA, Continuous improvement, Kaizen Activities, Poka Yoke, Process Activity Mapping, Self-Audits, Story boarding, Kanban, Scenarios, Takt Time, Lead Time mapping, Value Focused Thinking, Supplier Associations, Open Book Management	Measuring the effectiveness of lean thinking activities within maintenance
6	G. Clarke, G. Mulryan, P. Liggan, 2010	proactive maintenance, TPM, empowered action teams, SMED, 6S, Kaizen improvement, autonomous maintenance and distributed lean maintenance/MRO stores	Lean Maintenance–A Risk-Based Approach
7	T. Qiang, B. Zhu, L. Li, 2011	FMEA, Root Cause Analysis (RCA), RCM, TPM,CMMS, 5S, PDCA	A study on Military Equipment Lean Maintenance
8	Okhovat, M.A., Ariffin, M.K.A.M., Nehzati, T., Hosseini, S.A., 2012	visual control, 5S, seven wastes, Single Minute Exchange of Die (SMED) and Poka-Yoke (mistake-proofing)	Development of world class manufacturing framework by using six-sigma, total productive maintenance and lean,

Table 2.1: summary of related lean maintenance tools/ techniques. Source [33]

2.4.1 Types of maintenance wastes

The goal of lean maintenance is to cut waste. Any action that does not improve the machine's availability can be regarded as waste [34].

Overproduction: Refers to any unnecessary work that doesn't add value, such as conducting preventive and predictive maintenance tasks more frequently than required.

Poor Inventory Management: Results in inaccurate inventory levels, leading to the risk of stock-outs or unnecessary ordering of parts.

Transportation: Occurs due to ineffective planning and scheduling, resulting in unnecessary travel.

Waiting: Involves waiting for equipment availability, job assignments, tools, parts, instructions, permits, etc., which adds no value and should be minimized.

Process Waste: Arises from subpar repairs or insufficient time allocated for proper repairs.

Unnecessary Motion: Often found in preventive maintenance, where inspections should be based on equipment criticality to reduce unnecessary motion.

Defects: Leaving assets in unreliable conditions due to factors like inadequate training, outdated procedures, or lack of proper tools.

Under-Utilization of Resources: Refers to maintenance technicians engaging in non-value-adding tasks.

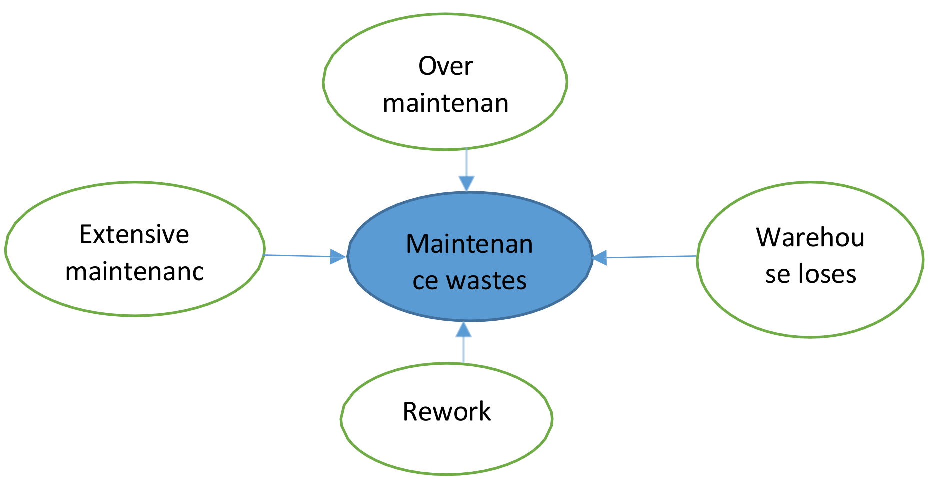

Figure: 2.3 wastes in maintenance. source [35]

2.4.2 Effectiveness or benefits of lean maintenance tools and restriction

There are three main known lean system benefits: operational, administrative and strategic improvements, [36], and also lean systems supports personnel creativity and reactivity. It also used for improvement of employee motivation, improve inventory management system, reduce lead time, improve production efficiency, improved labor productivity and customer satisfaction.

The efficiency of maintenance and repair operations can be improved, waste can be reduced or eliminated, and maintenance procedures can be updated through the utilization of lean maintenance technologies. Inspired by lean manufacturing principles, lean maintenance programs focus on restructuring schedules, minimizing non-essential tasks, and enhancing equipment reliability. As explained above the key tools like 5S, TPM, SMED, PDCA, RCA, Kaizen, VSM, reliability-centered maintenance, and Kanban are crucial for achieving this objective[37].

Lean maintenance plans, which are based on the principles of lean manufacturing, give priority to optimizing scheduling, cutting out non-essential work, and boosting equipment reliability. Although there are many lean tools available, six that are commonly used to apply lean and can significantly lower energy use have been discovered in waste to energy. Standard Work, Visual Workplace, TPM, Quick Changeover/SMED, Error Proofing/ Poka-yoke, Value Stream Mapping, and Right-Sized Equipment are some of these tools. The subsequent paragraphs demonstrate the substantial impact that the various tools discussed above can have on lowering energy use [38].

Tangible benefits

According to [39] the practical advantages of utilizing lean maintenance tools are substantial and impact various maintenance operations, resulting in enhanced efficiency, cost savings, and improved performance. Some of the tangible benefits achieved post the integration of lean tools include:

Extended Mean Time between Asset Failures: Companies can witness a significant extension in the mean time between asset failures, indicating enhanced reliability and decreased downtime.

Decrease in Urgent Maintenance Tasks: Lean maintenance approaches can lead to a more than 50% reduction in urgent maintenance tasks, demonstrating improved planning and minimized reactive maintenance.

Boosted Overall Equipment Efficiency (OEE): The implementation of lean maintenance tools can lead to a significant 13% increase in OEE, signifying enhanced equipment performance and productivity.

Enhanced Service Level in Storage Facilities: Organizations can maintain a consistent service level in storage facilities of up to 99%, ensuring effective inventory control and timely availability of spare parts.

Intangible benefits

The intangible benefits of implementing lean maintenance tools not related directly with financial achievement and include improvements in organizational culture, employee morale, and customer perception. These intangible benefits play a vital role in improving overall operational efficiencies and sustainability. Some of the intangible benefits of lean maintenance tools include:[5]

1. Better Teamwork: Lean maintenance tools promote association, communication, and teamwork among employees, fostering a culture of shared responsibility and continuous improvement
2. Improved Morale: By comprising employees in maintenance activities and allowing them to contribute to problem-solving and decision-making, lean tools can enhance morale and job satisfaction within the employees.
3. Enhanced Customer Perception: Implementing lean maintenance practices can lead to improved service quality, reduced downtime, and increased reliability, improve the overall opinion of the organization in the eyes of customers and stakeholders

2.4.3 Restriction of lean maintenance tools

According to [36] rather than benefits and advantage of lean tools it has also negatively affects the employees such as stresses, need much training and require hard working.

Most researchers agree that implementing a lean management system throughout an organization takes a lot of work, involvement from all levels of the hierarchy, and the introduction of new ideas not just at the shop floor but also in the enterprise culture and organizational structure. Due to the lack of clear rules and the fact that the procedure varies greatly from case to case, transitions can be sluggish, gradual, difficult, and stressful processes that may also cause a great deal of confusion [40]. Being a lean enterprise involves a dynamic process that is specific to each organization.

In addition to the above, the people spearheading and taking part in a Lean transformation currently possess a limited level of knowledge, frequently missing the restraints and intents of "real Lean," such as the following: (1) Lean is oriented to be a stakeholder-based system of management & not a management practice that promotes individual shareholder benefits at the expense of all other shareholders; and (2) negative cutting, like layoffs, is not the intent of Lean. In order to create stable and long-term growth, it should instead offer a means of generating new work, inspiring employees, and helping them reach their full potential rather than just eliminating jobs in the name of efficiency; (3) Lean principles can be applied to every business process [41].

2.5 lean Maintenance tools Elements and Measures

In power plants, similar to various industrial sectors, the focus of physical asset management is on minimizing maintenance costs while enhancing asset availability. Numerous strategies have been created and utilized to meet these objectives, including Total Productive Maintenance (TPM), Root Cause Analysis (RCA), proactive maintenance, and Reliability Centered Maintenance (RCM) [42].

Implementing a comprehensive and efficient predictive maintenance program stands out as a crucial tool for enhancing optimization and reducing costs in maintenance operations. Predictive maintenance involves an equipment intervention approach that relies on analyzing condition parameters to identify the optimal timing for necessary interventions [43].

From the exhaustive literature review the lean maintenance tools selected for the investigation in waste-to-energy power plant which contributes significant role towards operational performance include:

5S Process: The 5S process is fundamental to lean maintenance and involves steps that regular personnel can follow to support maintenance processes

Total productive maintenance (TPM): Lean processes and principles can support a program for total productive maintenance (also known as total preventive maintenance). TPM involves taking an organized approach to preventive maintenance with the goal of eliminating defects, breakdowns, accidents, and waste

Mistake-Proofing: Implementing plans and procedures to minimize mistakes and errors, ensuring efficient maintenance operations and resource utilization

Kaizen Events (continuous Improvement): Eliminating waste ensures that your equipment and your team are operating at peak capacity. This will ultimately establish a workplace culture characterized by engagement and commitment to lean principles like continuous improvement. With less time spent on non-value-adding work, your maintenance team will have more time to focus on what really matters. You’ll gain access to valuable performance insights that can help facilitate process improvements as your lean maintenance program evolves.

Self-Directed Teams: Lean maintenance relies on self-directed teams performing tasks efficiently and autonomously, enhancing overall maintenance effectiveness

CMMS (Computerized Maintenance Management System): Utilizing a CMMS can streamline maintenance planning, scheduling, work order management, and data analysis, contributing to lean maintenance practices

Continuous Analysis: Regularly analyzing maintenance processes to identify areas for improvement, optimize workflows, and ensure lean practices are effectively implemented

VSM: improve the flow of materials and information required to bring a product or service from supplier to customer. Value stream mapping provides a comprehensive view of the entire process, including both value-adding and non-value-adding activities, helping organizations identify areas of waste and opportunities for improvement.

SMED: it's designed to reduce the time it takes to switch from making one product to another on a production line. By applying SMED, companies can significantly reduce down time, increase flexibility, and improve productivity. It's all about making quick and efficient changes.

JIT: aimed at minimizing inventory and production costs by producing goods only as they are needed

Predictive maintenance: is the part of planned maintenance activity strategy used to forecast or predict when equipment or machinery is likely to fail, so that maintenance can be performed just in time prevent the failure from occurring.

In order to evaluate the operational performance dimensions grow as a result of effective emphasis of lean maintenance tools, a five point scale will be used in this study to show the status of correlation (rating mechanism : 1- no correlation at all, 2- nominal impact, 3- same impact, 4- reasonable impact, 5- extensive impact).

Six Sigma: Process optimization, defect discovery and elimination, and overall performance optimization are all aided by Six Sigma [44]. Manufacturing organizations can increase operational performance by reducing variability and errors in their processes through the implementation of Six Sigma.

No	Lean Tools	Description
1	5s	Eliminate wastes that results from poorly organized work area
2	Andon	Acts as a real time communication tool for the plant floor that brings immediate attention to problems as they occur
3	Bottleneck Analysis	Improves throughput by strengthening the weakest link in the manufacturing process
4	Continuous flow	Eliminates many forms of waste such as inventory, waiting time etc..
5	Cellular Manufacturing	Supports continuous flow by calling on teams to arrange workstations based on the parts they produce in order to minimize travel time
6	Gemba (The Real Place)	Promotes a deep and through understanding of real world manufacturing issues
7	Heijunka (Level Scheduling)	Reduces lead time (since each product or variant is manufacturing more frequently) and inventory (since batches are smaller)
8	Hoshin Kanri (Policy Deployment)	Eliminating the waste that comes from poor communication and inconsistent direction
9	Jidoka (Automation)	Workers can frequently monitor multiple station (reducing labor cost) and improving quality
10	Just in time (JIT)	Highly effective in reducing inventory levels and improves cash flow and reduce space requirement
11	Kaizen (Continuous improvement)	Combines the collective talents of a company to create an engine for continually eliminating waste from manufacturing process
12	Kanban (pull system)	Eliminates wastes from inventory and overproduction
13	KPI (key performance indicators)	Important and powerful derivers of behavior
14	Muda (waste)	Anything in the manufacturing process that does not add value from the customer perspective
15	OEE (Overall Equipment Effectiveness)	Provides a benchmark/baseline and a means to track progress in eliminating waste from the manufacturing process
16	PDCA (Plan, Do, Check, Act)	Applies a scientific approach to making improvements
17	Poka-Yoke (Error proofing)	Design error detection and prevention into production process with the goal of achieving zero defects

18	Root cause analysis	Helps to ensure that a problem is truly eliminated by applying corrective action to the root cause of the problem
19	SMED (Single Minute Exchange of Dies	Enables manufacturing in smaller lots, reduces inventory and improves customer responsiveness
20	Six Big Losses	Provides a framework for attacking the most common causes of wastes in manufacturing
21	SMART Goals	Helps to ensure that goals are effective
22	Standardized work	Eliminates wastes by consistently applying best practices and forms a baseline for future improvement activities
23	Takt time	Provides a simple, consistent and intuitive method of pacing production
24	TPM (Total Productive Maintenance)	Creates a shared responsibility for equipment that encourages greater involvement by plant floor workers and improve productivity by increasing up time, reducing cycle time and eliminating defects
25	VSM(Value Stream Mapping)	Exposes wastes in the current process and provides a roadmap for improvement through the future state
26	Visual factory	Makes the state and condition of manufacturing process easily accessible and very clear to everyone

Table 2.2: Summary of lean tools

2.6 Operational Performance

According to [45] “operational performance (OP) refers to the manufacturing plant's ability to produce and deliver products to customers more efficiently”. Operational performance conventionally discussed from the aspect of priorities of strategic operational Competition in the manufacturing industry. According to [46] the most popular measures for assessing OP are costs, efficiency, execution, productivity, inventory level, creativity and adaptability. As such, the creation and regularity of new product introductions were included in a list of indicators. In order to increase productivity, nearly half of the businesses collaborate closely with suppliers, customers, and technology centers.

In the industrial sector, operational performance is typically examined from the perspective of strategic operational competitiveness priorities [47]. Prioritizing competition is a crucial aspect of any process or supply chain when it comes to satisfying current and potential customers, whether they are internal or external. Quality, delivery, flexibility, and cost are the four primary components that most researchers used to measure operational effectiveness in the manufacturing industry [47].

MSW power plant operating efficiencies were consistent with their operational performance, including operation hour or availability and power generated volume, even though they depend on plant scale, steam parameters, steam usage efficiency, and MSW characterization (e.g. calorific value). Some biological leftovers, such as sewage sludge from food processing, can be supplied to co-incinerate with MSW to improve the efficiency of WTE plants since they have a high concentration of biological components.

Operational efficiency is calculated as: OE = P/W, where OE= operational efficiency, p = represented total energy generated, W= represented quantity of waste incinerated

Plant availability is the amount of time that a certain plant or piece of equipment can be used to accomplish its intended purpose. It can be expressed as the percentage of actual operating time relative to the total amount of time observed, and it measures the likelihood that the equipment is in operational condition. In manufacturing, availability is a critical statistic that affects operational performance by optimizing production time and reducing downtime.

2.7 Operational performance elements and measures

Regular monitoring, analysis, and improvement efforts based on performance elements and measures are essential for optimizing the operation of MSW power generation plants and ensuring their long-term sustainability and effectiveness [48]. In this study, the criteria to measure the operational performance dimensions are: maintenance downtime, maintenance cost, availability, energy generation volume, and efficiency.

Maintenance downtime: tracking scheduled maintenance activities and unplanned downtime for maintenance or repairs, aiming to minimize disruptions to operation.

Quality: reduce quality problems by minimizing defects, and continuously improving processes to ensure consistency and reliability.

Efficiency: the ability to produce goods or deliver services using the minimum amount of resources, such as time, labor, materials, and energy while maximizing output and minimizing waste.

Availability: refers to the proportion of time that the production system, equipment, or machinery is operational and available for work during scheduled production hours. From WTE point of view is the measure of the percentage or probability of time the plant is operational or machine uptime and producing energy without unplanned downtime.

Cost (Maintenance cost): the expenses incurred to keep equipment, machinery, facilities, or infrastructure in working condition and to protect unexpected failures or breakdowns.

Customer satisfaction:

Safety Performance: Ensuring adherence to safety protocols and regulations to protect workers, equipment, and the surrounding environment from accident or hazards associated with WTE operations

No	Tools	Measuring categories
1	Quality	Productivity, product quality, process performance& durability
2	Delivery	Efficiency, speed, flexibility, responsiveness, reliability, timely delivery, flexibility and customer satisfaction
3	Cost	Scrap/waste, cost of maintenance, energy/ efficiency cost and cost of quality
4	Innovation	Process innovation, product innovation, radical and incremental
5	Capacity utilization	Plant efficiency, design utilization and productivity
6	Defects	Parts per million and sigma level
7	Inventory	Holding cost and on time flow

Table 2.3: List of Operational Performance Measures, Performance Indicators and Supporting References[1].

2.7.1 Key Operational Performance Indicators (KPI)

Operational performance can be measured using various key performance indicators (KPIs) when implementing lean maintenance tools. Lean maintenance focuses on eliminating waste, optimizing processes, and improving efficiency. Here are some key performance indicators relevant to measuring operational performance in a waste-to-energy facility [49]:

Equipment Availability:

KPI: Overall Equipment Effectiveness (OEE)

OEE measures the overall efficiency of equipment by considering availability, performance, and quality. High OEE indicates minimal downtime and optimal equipment performance.

Downtime Reduction:

KPI: Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR)

Reducing the time between equipment failures (MTBF) and minimizing the time it takes to repair equipment (MTTR) helps maximize equipment availability.

Preventive Maintenance Compliance:

KPI: Percentage of scheduled preventive maintenance completed

Measures the effectiveness of planned maintenance activities in preventing unplanned downtime and reducing the likelihood of equipment failures.

Energy Efficiency:

KPI: Energy consumption per unit of waste processed

Tracks the efficiency of the energy conversion process, helping to identify opportunities for energy savings and process optimization.

Waste Throughput:

KPI: Tons of waste processed per unit of time

Measures the facility's capacity to handle and process waste efficiently. Increasing throughput without compromising safety and environmental standards is a key goal.

Inventory Management:

KPI: Inventory turnover rate for spare parts

Efficient management of spare parts inventory ensures that necessary components are available when needed, reducing downtime caused by waiting for replacement parts.

Labor Productivity:

KPI: Maintenance hours per unit of waste processed

Evaluates the productivity of the maintenance team in relation to the amount of waste processed. A decrease in maintenance hours per unit of output may signify improved efficiency.

Cost of Maintenance:

KPI: Maintenance cost as a percentage of total operational costs

Monitors the proportion of operational costs attributed to maintenance. A decrease in this percentage may indicate cost-effective lean maintenance practices.

2.8 Lean maintenance tools relationship with operational performance

Lean maintenance tools and operational performance are closely related, which is crucial for increasing productivity, decreasing downtime, and cutting waste. By using lean maintenance techniques, company can become more competitive and profitable in both short and long run.

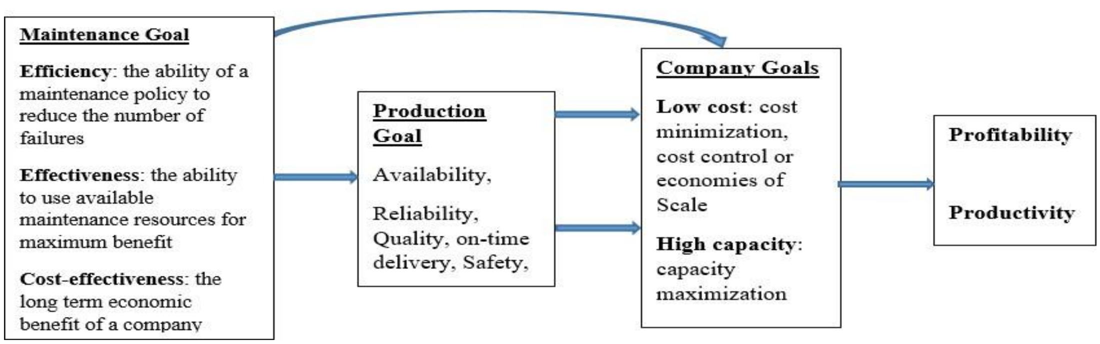

Figure 2.4: connection between maintenance with profitability and productivity

The relationship between Lean Maintenance Tools and operational performance is interdependent. Lean Maintenance Tools provide the framework necessary to enhance operational efficiency, while improved operational performance, in turn, supports the successful implementation of these tools. The systematic application of Lean Maintenance Tools results in increased productivity, reduced downtime, and enhanced asset reliability, all of which positively impact operational performance metrics

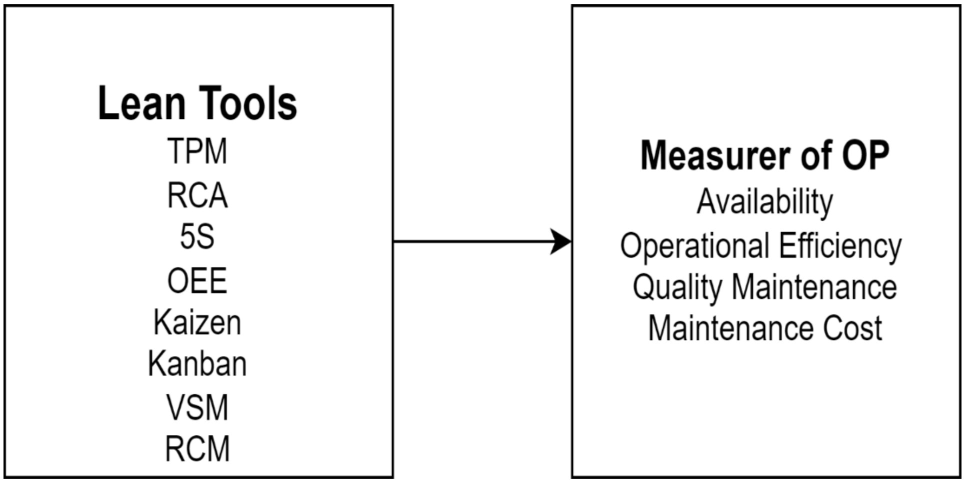

Figure: 2-5 Lean maintenance relation with OP

2.9 Framework of Lean maintenance tools

A framework can act as a guide and it provides a pre-built structured and a set of tools that provide a foundation for developing applications. A review of literature revealed that different frameworks of lean maintenance tools are available. But very few frameworks or none were proposed by researchers for waste-to-energy.

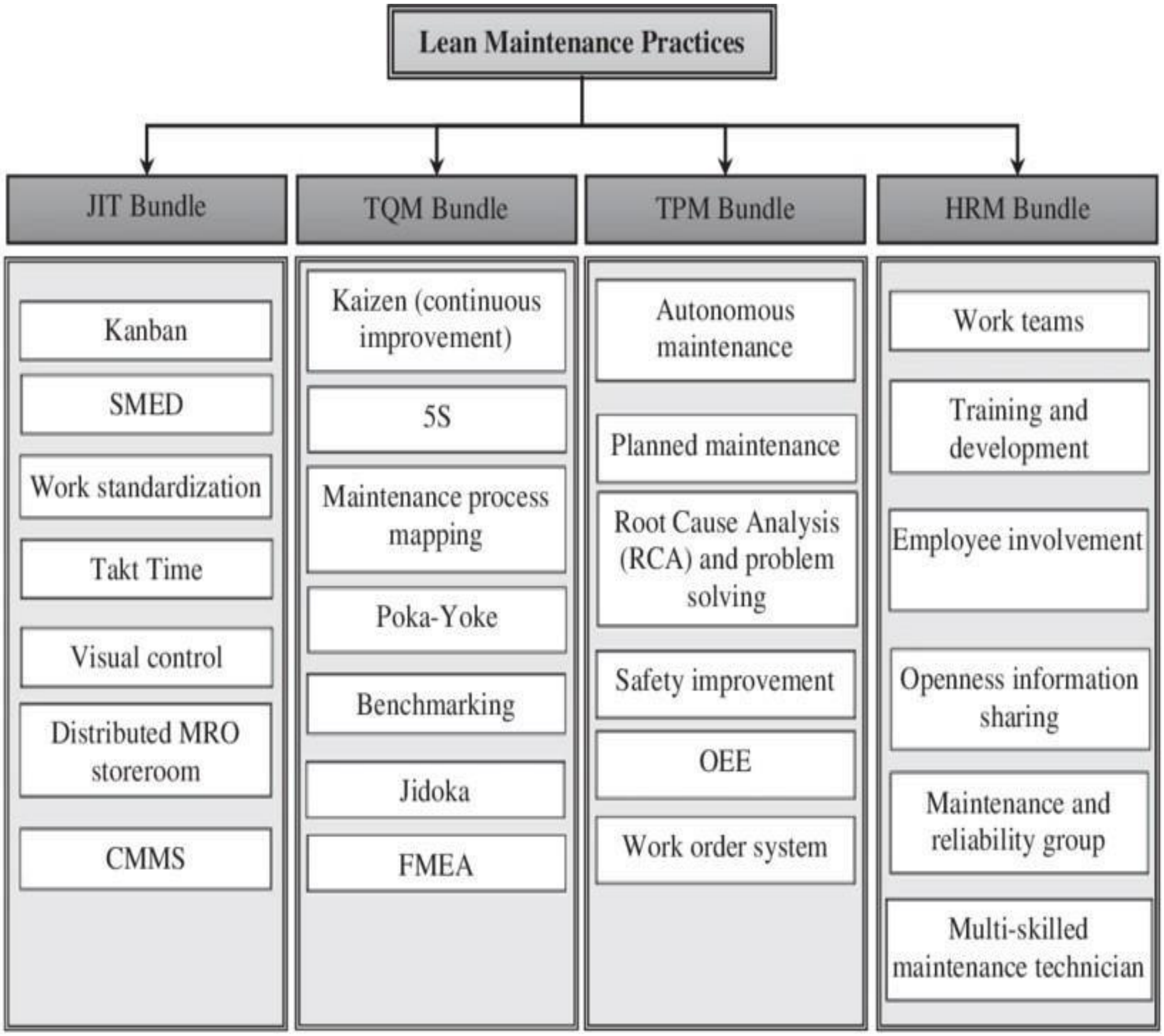

Figure 2.6: schematic for lean maintenance practice [7]

2.10 Summary of the literature

The definition of lean and operational performance, lean manufacturing, lean operation and lean maintenance are raised in this topic. The usefulness of lean maintenance tools elements and operational performance are also seen. To get enough information about the topic raised many kinds of literatures are reviewed from different sources, among these journals and articles. During literature survey recent documents concerning lean maintenance and operational performance were collected from different sources then try to see the gaps. The below table summarizes main articles with regard to lean maintenance and operational performance

Author	Title	Product analyzed	Technique used	Benefits derived	limitation
E. Kosicka, A. Gola, and J. Pawlak, 2019	Application-based support of machine maintenance,	General manufacturing organization	TPM pillar	improving product quality and productivity	Focused on human factor only
A. Igodo, A. Shamsuzzoha, E. Ndzibah, and M. Shamsuzzaman,2023	Optimal maintenance for a waste-to-energy	waste-to-energy	DEMATE L	Optimized maintenance program	The problem is not clearly stated
S. Mostafa, S. H. Lee, J. Dumrak, N. Chileshe, and H. Soltan,2015	Lean thinking for a maintenance process,	Manufacturing organizations	Lean QFD	Integrate lean principles & maintenance strategy	The findings of this study cannot be generalized
T. Pombal, L. P. Ferreira, J. C. Sá, M. T. Pereira, and F. J. G. Silva, 2019	Implementation of lean methodologies in the management of consumable materials in the maintenance workshops of an industrial company	Workshop	Lean	Optimize consumable material usage	Not considering the company's overall equipment maintenance
M. A. Sayid Mia, 2017	Implementation of Lean Manufacturing Tools	Shoe	Problem solving methods	Waste minimized	The result observed is not clearly stated
O. Devi and D. K. Putu, 2020	"Improving Overhaul Process on Steam Power Plants using Lean Thinking and LCA	Power plant	lean	Consider process flow	Not considering different types of operation performance
A. Irajpour, A. Fallahian -Najafabadi, M. A. Mahbod, and	"A framework to determine the effectiveness of	Not limited to case company	DEMATEL and TOPSIS	Optimized maintenance model	Not considering The known

M. Karimi, 2014.	maintenance strategies lean thinking approach,"				performance of a case company
I. Al Mouzani and D. Bouami, 2019.	"The integration of lean manufacturing and lean maintenance to improve production efficiency,"	Manufacturing organization	lean	Stated Lean maintenance is the prerequisite of lean manufacturing	
I. Chinhengo, W. M. Goriwondo, and B. Sarema, 2020.	"Application of lean tools in planned maintenance: case study of a coal handling plant at a thermal power station	Coal	VSM	Maintenance waste identified	Used only one lean tool
T. Le Phong and N. D. Minh, 2022.	"Integration of Lean Methodology and Energy Management in Wooden Industry	Wood	Lean	Energy consumption reduction	The improvement by lean tools was not clearly stated
O. Duran, A. Capaldo, and P. A. D. Acevedo, 2017.	n maintenance applied to improve maintenance efficiency in thermoelectric power plants,"	Power plant	Fuzzy-AHP	Maintenance waste reduction	Limited to only for types of waste
A. Ishak and E. Mohamad,2023.	"Application of Lean Six Sigma for Enhancing Performance in the Poultry Wastewater Treatment,"				

S. Rahman, T. Laosirihongthong, and A. S. Sohal, 2010.	"Impact of lean strategy on operational performance: A study of Thai manufacturing companies,"	Manufacturing company	Multiple regression model	Waste reduction	The study was not included large industries

Table 2.4: Summary of main articles

2.11 Selected Tool

Different techniques of multi criteria decision making (MCDM) approach were applied by the researchers in prioritizing the lean tools. Based on the observed literature gaps, the researcher has selected MCDMs called AHP technique for the prioritizing lean maintenance tools selection [50].

The AHP problem solving process could identify three principles: decomposition, Comparative judgment and the synthesis of priorities.

The Analytic Hierarchy Process (AHP), founded by Thomas Saaty, proves to be a valuable asset in handling complex decision-making processes. It facilitates decision-makers in establishing priorities and arriving at optimal choices. Through a systematic approach of minimizes complex decisions into alternate comparisons and subsequently integrating the outcomes, AHP accurately incorporates both subjective and objective factors into the decision-making process.

The AHP offers a method to break down the problem into a hierarchy of sub-problems, making it easier to understand and subjectively assess them. These subjective assessments are transformed into numerical values and then analyzed to rank each alternative on a numerical scale ([51]

The key AHP methodology steps are as follows:

1. Developing the hierarchical structure of the decision problem: The problem Decomposes into a hierarchy at the first level the objective, next criteria/sub criteria and finally alternatives.
2. Pairwise comparison: Once the hierarchy has been defined; the relative importance between the two criteria is measured according to the fundamental scale of [52] The scale of 1-9, with 1-Equal importance; 3-Moderate importance; 5- Strong importance; 7-Very strong importance; 9-

Extreme importance and the others are intermediate values between two adjacent judgments. The same procedure is repeated for each criteria combination.

3. Matrix for the decision problem: The matrix has m as order and is the number of criteria. The matrix organizes a diagonal element as one, all elements are positive, and the lower triangular part has reciprocal values of the upper triangular. The matrix A elements as ajk represents the importance of the jth criterion relative to the kth criterion and organize in the jth row and the kth column of matrix A.
4. Establishing priority weight: The priority weights calculated from individual pairwise comparisons are normalized and integrated into a matrix that indicates the relative priority or importance between items for achieving the goal.
5. Consistency check: to ascertain the judgment consistency was calculated the consistency Index (CI), random index (RI) and consistency ratio (CR). The CI was calculated by (λmax - n)/(n - 1), where λmax is the maximum Eigenvalue and n is the size of the matrix. The RI is an experimental value that depends on n, and for this study is 0.89. Finally, CR was calculated by CI/RI and must be lower than 0.10 for an acceptable level of consistency.

The individual judgments were aggregated by aggregating individual priorities (AIP) method, the process of group experts' using geometric mean calculation

2.11 .1Justification to select & use AHP from other MCDM tools

A few reasons why AHP selected and used by this study: [53]

1. **Intuitive and easy to use: -** People don't feel comfortable taking recommendations from Software if they don't understand how it works. They don't need to know the details but they Want to understand the idea behind it.
2. **Designed for multi-criteria:-** When you make important decisions, there are always conflicts Between criteria. Analytic Hierarchy Process allows us to take into account all important Criteria and to organize them into a hierarchy.
3. **Validates consistency: -** We are all humans and it's our prerogative to be inconsistent Sometimes. We make mistakes. When we make collaborative decisions there are multiple People that can make mistakes and be inconsistent. AHP can eliminate a wonder of group Decisions by aggregation method. We deliver redundant data (more than needed) and an Algorithm checks to see if your input is consistent.

2.12 Literature Gap

Numerous studies have been done about plant efficiency improvement and equipment availability by using lean tools and techniques, but very less or none have been done on operational performance improving by using appropriate lean maintenance tools selection which are valuable for removal of non-value adding in waste-to-energy facilities. For Reppie waste to energy power plant different studies were conducted; but related to waste treatment and flue gas treatment system only [8]. However, there is a big gap, lack of study about the operational efficiency improvement by optimizing cost, machine uptime and availability of Reppie waste to energy power plant. [9] States that there is a limitation of studies that shows the relation or influence of one company's KPI challenges on other performance.

On the other hand different literatures conducted operational performance analysis of the waste to energy power plant by considering the energy generated to the amount of waste input [54]. This lacks an inclusive discussion on how the prioritization of lean maintenance tools can significantly contribute to the improvement of operational performance by considering different performance measuring elements in WTE plant.

However, the existing literature lack a focused approach on selecting lean tools by prioritizing lean maintenance tools which have most affecting the operational performance for waste to energy, specifically in Reppie waste to energy.

CHAPTER THREE

3. Research Methodology

3.1 Introduction

Methodology refers to a systematic way to conduct a research that containing various techniques of data collection, methods and tools of analyzing the data to achieve the objectives of the study. This chapter discusses an overview of the approaches adopted for the methods employed in the study. The areas covered include the research design, sources of data, and instruments of data collection, population and sampling procedures, and methods of data analysis.

3.2 Research Design

There are different definitions of research designs; according to [55] "it is the blueprint for fulfilling research objectives and answering questions where it aids the researcher in the allocation of limited resources by posing critical choice in the methodology". [56] Believe that even though choosing the right research design can be challenging, by combining different approaches, researchers can gain deeper understanding than if only used techniques that are frequently used or that have received the most attention from the media.

[57] Says that the descriptive research approach minimizes bias and increases the dependability of the data gathered and examined when the goal is to accurately describe a scenario or an association between variables. The process of gathering information to address questions about the present state of the topic study is known as descriptive research. As a result, the descriptive research design allows the researcher to collect information from a variety of respondents regarding the topic.

It is crucial to choose vital design for a research study which entails a careful consideration of the future phenomenon under investigation. The goal of this thesis is to maximize an equipment's service level while minimizing its overall downtime and associated maintenance costs to increase overall operational performance. The research design used for this study is a descriptive case study research since the study focus is in a particular case company which is **Reppie waste-to- Energy power generation plant**. The descriptive research method aids in the development of a reliable overall conclusion.

Documented information was considered to discuss the concepts and identify reasons and gaps in analysis of the case company's operational performance and the prepared survey question considers

both quantitative (for quantification of variables) and **qualitative** (to identify the nature of the cause of variables) then rank lean for maintenance using a decision tool AHP (analytical hierarchy process). It is an effective tool to achieve the objectives of such complex decision making.

3.3 Data Collection Methods

Data collection is the process of gathering information's that are relevant to accomplish the study. In this study structured questionaries, interviews and observations were used for the researcher to gather data. There were two sections of structured questions used on the questionnaire. In part I, the respondents' demographic background was covered. Part II of the question covers respondents' opinions of the effectiveness of the plant impacts of selecting and using specific lean tools and OP based on key dimensions questions.

Both primary and secondary data collection was used in the research by the researcher. Under this two methods literature review, interview, questionaries and observations have been used.

3.3.1 Primary Data Collection

It is one of the methods used in this research. Under primary data collection the three mostly used methods which were observations, interview and questionnaires.[58] Argues that this types of collection design is similar to the types of questions that leads to the outcome.

a. **Observation**

Observation is one way of primary data sources. It's a method of watching and listening to an interaction or phenomenon where it takes place. In order to understand the facts about the case company actual production process and maintenance activities i.e. how exactly the existing system is working, lean maintenance activities used, the situations that the company doing things, how technicians perform their maintenance routines and others things related to maintenance activities have been observed.

b. **Interview**

Interview is one of the tools used to gather data. Due to its useful in achieving high response rate and in obtaining detailed information about perceptions, feelings, and opinions of the person that is going to be interviewed, this method have been used in this study.

c. **Questioners**

Questioners are the main tools in collecting data. The researcher has developed questions considering the actual performance of the company and the lean tools application level for enhancement of operation performance selected for this study and other related issues included.

3.3.2 Secondary Data

In addition to primary data secondary data was collected from the case company reports, documents and also from the literature regarding the research areas.

A. **literature reviews (previous Research)**

The study was began with a comprehensive review of existing literature on lean maintenance practices, suitability and application in this sector, and its impact on operational performance and energy generation.

B. case company documents

The researcher has gone through the company profile like factory organization chart, maintenance organization chart, the company's maintenance policy, work order books, different performance reports and other relevant reports has collected as a secondary data.

3.4 Research population and Sampling procedures

The group that the researcher is interested in learning more about and from which the sample has been taken is referred to as the population. The critical part of the research is the way that we have selected a sample of individual.

Target population

The population refers to a total group of individuals or objects that researchers are interested.

Even though, the total employee in the company is around 110 but 50 of them are drivers and daily labor (cannot read and write). Accordingly, in this research the target population selected for the study is as shown in the table below.

Managers and staff members in operation and maintenance departments were included in the study to ensure a representative and pertinent sample size that supports the research findings.

Sampling techniques

Purposive sampling

When a researcher wants to examine a small group of individuals with expertise and understanding in the field, they employ this kind of sampling technique. Purposive sampling has thus been employed by the researcher because the research area included individuals with expertise.

According to [58] a minimum of 10% of large populations and 20% of small populations can be taken as sample size. However, in order to obtain more trustworthy data from a variety of respondents, the researcher has used sampled of 40 (forty) percent of the target population.

Based on that, 1 operation manager and 4 operation shift leaders from operation department, 1 maintenance manager and 5 maintenance Engineers were selected through probability sampling. In addition to that, 11 SCADA operators, 8 maintenance technicians and 2 quality inspectors were taken as sample respondents for interview questions.

NO	Type of Respondents	Total Population Size	Sample size	Category of sampling technique
1	operation manager	1	1	Random sampling
2	shift leader engineers	4	4	Random sampling
3	maintenance manager	1	1	Random sampling
4	maintenance Engineers	6	5	Random sampling
5	SCADA operators	30	11	Random sampling
6	maintenance technicians	15	8	Random sampling
7	quality inspectors	3	2	Random sampling
8	Total	60	32	

Table: 3.1 Total population and sample size

3.5 Data Analysis Method

The data analysis in descriptive methods research refers to the types of research strategy chosen for the procedures. Both data from the existing company and questionaries was analyzed by using Microsoft Excel 2010 and SPSS.26.0 version software; which is used to maintain the database and for the descriptive data analysis. The data gathered from various sources has been compiled, arranged into categories, and coded according to the sample strategy section to suit for analysis, while the closed-ended questions were coded and subjected to both descriptive and inferential statistics, using AHP, percentages, frequencies, tables, and Pareto analysis. The qualitative or open-ended questions have been condensed and presented exactly as they are. Accordingly, the SPSS was employed to ascertain the degree of significance of the respondents' response differences. In addition to descriptive analysis, analytic hierarchy process (AHP) is used to prioritize the tools and help the decision of selecting more significant rank of tools. Moreover, AHP tool is also used to investigate and rank the relationships between lean maintenance tools and operational performance KPIs. The end result has been presented in a written form and in the form of table. Finally, presentation, analysis, and interpretation of data, framework development and conclusions and recommendations was drawn using analysis and data outcomes into a text format.

The initial step in the development of a framework was to understand the topic, to understand how the concepts are related, to examine the different frameworks relevant to the study, to investigate the case to understand the existing working conditions and compare with the literature, to select, develop or modify the existing one. Methods that can be adapted to the company of the case. After developing an implementation step, discuss to help technical experts and managers to validate the framework.

No	Item of data	Method of analyzing	
		Tools	
	Open ended interviews for both production and maintenance manager & planner	Description	These qualitative data entertained based on their frequency
2	Closed ended questioner for shift leaders, maintenance supervisor, technicians and operators	SPSS 24.0	Scale, percentage, mean, & standard deviation treated quantitatively
3	Observation check list of the factory operation status and break down time related documents	Tables & charts	Here researcher observed the factory refurbishment maintenance area, downtime history and efficiency and then analysis will be done using quantitative method (tables, and charts)

4	Lean tools and Operational performance dimensions	Analytic hierarchy process	Prioritizing the tools to support the result drown from descriptive analysis by using tables % Pareto
5	Analysis Result	Visio	Table & Graphical

Table 3.2 method of data analyzing

3.6 Reliability and validity

Methodological triangulation was used to increase the study's validity and reliability through the use of key informant interviews, semi-structured questionnaires, and structured questionnaires. The goal of triangulating the research approach is to see if comparable findings can be obtained using other techniques for gathering data.

The degree of education, technical proficiency and technological awareness, organizational hierarchy, and other vested personal and professional interests are likely to influence how different organizations and employees view the circumstances, opportunities, and challenges. Therefore, throughout the sample selection process, an attempt was made to choose employees from the organization using a random deliberate sampling technique.

Additionally, this thesis employed a variety of data gathering and analytic techniques in order to capture the differing viewpoints that were collected from various stakeholders.

3.7 Research Framework

Data collected, sorted, organized and coded

This research was a case study type from RWTE whereby quantitative and qualitative was collected for analysis. The general flow plan of the methodology is visualized in figure, which gives an understanding on how the method suits the stated objectives

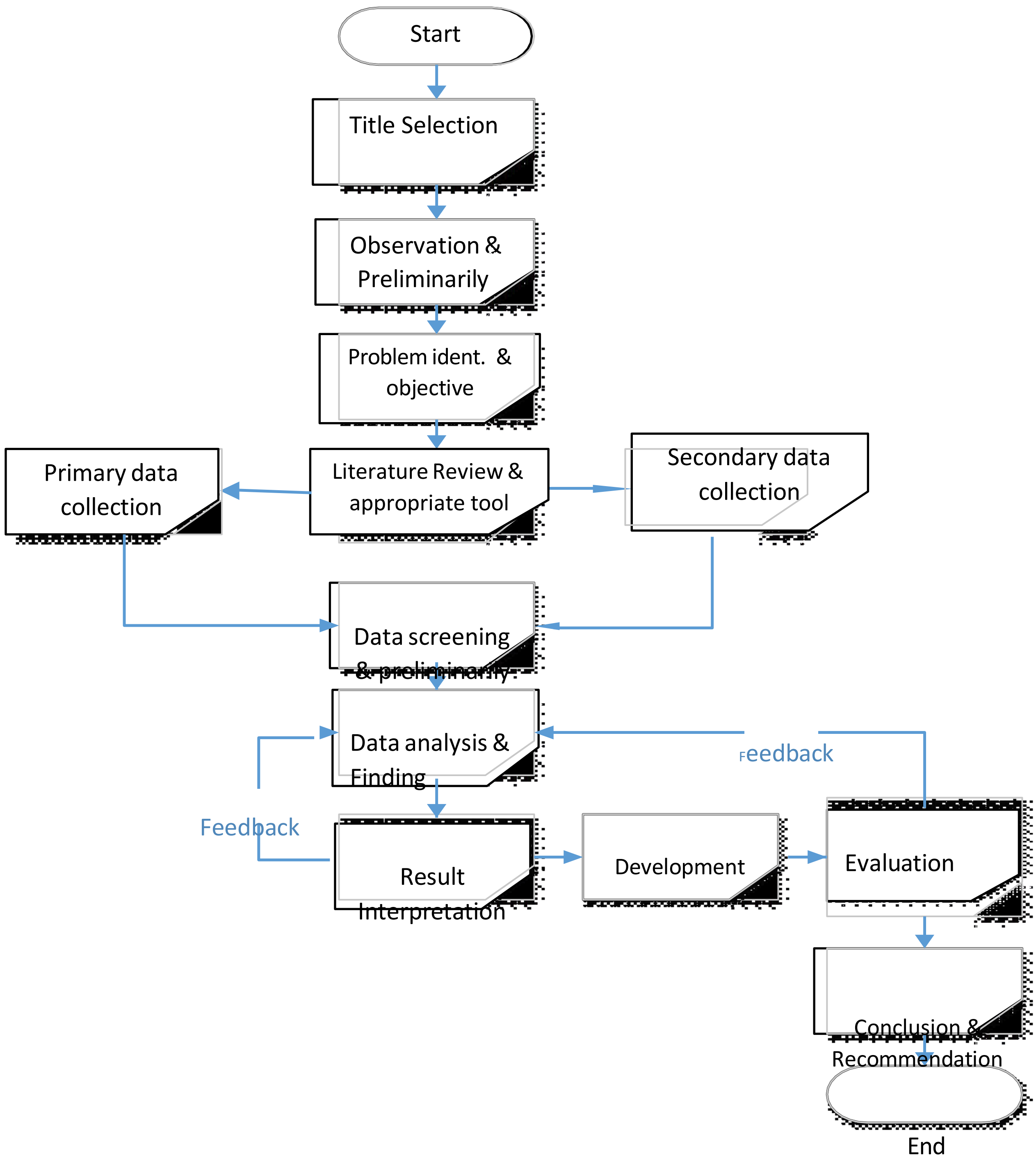

Figure 3.1: Research framework Design chart

CHAPTER FOUR
4. Results and Discussion

4.1 Introduction

This chapter contains data analysis, summary of data findings and their interpretation. The analysis was done by the collected data in detail and gives an indication to concern with research objectives.

To get the right result from the given selection criteria, reliable data collection & analysis have the vital role. In this research study, data will be collected through direct observation, questioner & interview from the company's expertise & managements. As discussed in previous session, for the researcher to proceed with the data collection, it must be known what data should be considered for lean maintenance tools selection criteria and decision making using AHP tool. Accordingly the survey questionnaires data analysis, presentation and discussion of the results are presented as follows:

4.2 Data Collection (survey questionnaires) and Analysis

4.2.1 Determination of the sample size

AHP depends on the types of problem that we have handle and it is different from condition to condition. According to [59], we have just assumed to get experts opinion related to sectors & organization has a minimum of three and a maximum of five expert opinion

In this study, as listed in table 3.1 the researcher used seven types of respondents and a total of 32 participants. As per the distributed questionnaires for 32 participants, the collected questionnaires were 100%.

4.2.2 Distribution, Collection of the questionnaire and interview question.

The AHP Alternative from which the data were to be considered as an input to the selection criteria to the tool were selected by the case company's different departments experts. This focused groups considered personnel with more than three years of experience in each departments and have familiar with operation process and machine history. The team were comprised of plant manager, maintenance manager, Operation manager, mechanical specialist, Electrical & instrument specialist, chemical laboratory experts, maintenance technician and DCS operators. The first section were about the general information of the participants regarding educational background, experiences in the company and their working position. The second and third parts of the questionaries were about the consideration of selected Lean maintenance tools and Operational performance tools for consideration and interpretations of the tools.

The collected data was analyzed using MS excel, and SPSS 26.0 software and the result was prepared as follows. The first part of the question was preliminary information which asks professional level, work experience, marital status and others.

4.3 Analysis of the Current Status of Operational Performance of RWtE Plant

When came to the result of professionals, 7 of them had college diploma or technic, 21 had BSC degree and 4 of them had Master degree. When came to work experience, 14 of them had 3-5, 14 had 5 to 10 and 4 of them had above 10 years' experiences.

In order to understand and evaluate the actual problems facing the company operational performance, detailed statistical data was collected from the company, which was then compiled and analyzed. The data represents production time of 2022/2023 fiscal year. Table 4-1 presents the operation target, downtime of one year and its type.

Reason For down time in hours for a fiscal year 2022/23

Months	working hour target(WHT)	Electrical Failure	Mechanical Failure	Power Outage	Other Failure	Total Down Time hours (TDH)	Proportion of Down time TDH/WHT
July	602	96	135.33	0	0	231.33	38%
August	602	0	602	0	0	602	100%
September	602	0	602	0	0	602	100%
October	602	491.45	105	5.55	0	602	100%
November	602	0	168	0	0	168	28%
December	602	21	581	0	0	602	100%
January	602	18.83	310.34	0	251.3	580.87	97.06%
February	602	40	344.34	0	0	384.34	64%
March	602	100	428	0	0	528	88%
April	602	301	301	0	0	602	100%
May	602	330		0	0	330	55%
June	602	432	105	0	0	537	89%
Total	7224	1830.28	3682.01	5.55	251.3	5769.54	79.92%
		25.33%	50.96%				80%

Table 4.1: statistical data for downtime and failure for the year of 2022/2023

From the table above the downtime of the stated year is between 28 % and 100%. The power outage was when the supply of electricity interrupted which was mainly caused by grid disturbance and it is outside the control of the company, it was relatively limited number of hours 5.55 hours per year.

The majority of nonproductive time or downtime seen on table 4.1, is mainly caused by Mechanical failure, it accounts about 50.96% of the total target working hours. This implies that there is no maintenance wastage identified and carried on the machines. The second major down time is electrical failure, this is also mainly due to the failure due to the lack of quality maintenance that is not parallel with the skill level of the machines sophistication.

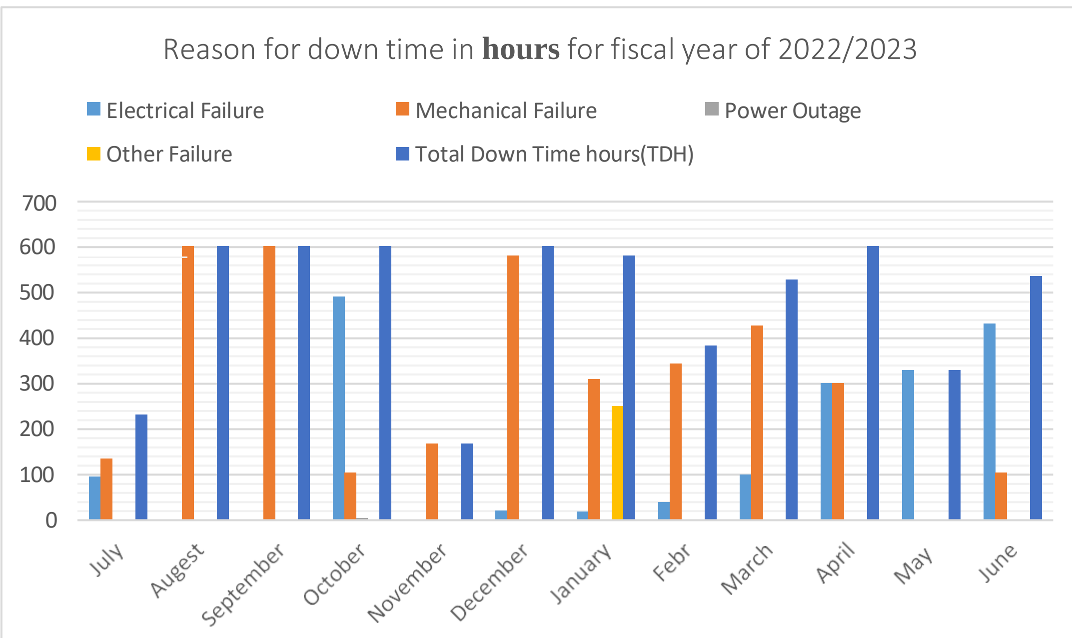

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Figure 4.1: Reason for down time in hours for fiscal year of 2022/2023

comparison of production with target and actual and down time level on 2022/23							proportion of actual with	
months	Unit	Design capacity	target production	actual production	down time	proportion of down time	Design (%)	Target (%)
July	MWH	18,120.0	15,120.0	0	15,120.0	#DIV/0!	0%	0%
August	MWH	18,120.0	15,120.0	0	15,120.0	#DIV/0!	0%	0%
Sept.	MWH	18,120.0	15,120.0	0	15,120.0	#DIV/0!	0%	0%
October	MWH	18,120.0	15,120.0	0	15,120.0	#DIV/0!	0%	0%
Nov.	MWH	18,120.0	15,120.0	560	14,560.0	2600%	3%	4%
Dec.	MWH	18,120.0	15,120.0	0	15,120.0	#DIV/0!	0%	0%
Jan.	MWH	18,120.0	15,120.0	110	15,010.0	13645%	1%	1%
Feb.	MWH	18,120.0	15,120.0	497.5	14,622.5	2939%	3%	3%
March	MWH	18,120.0	15,120.0	640	14,480.0	2263%	4%	4%
April	MWH	18,120.0	15,120.0	0	15,120.0	#DIV/0!	0%	0%
May	MWH	18,120.0	15,120.0	3147.5	11,972.5	380%	17%	21%
June	MWH	18,120.0	15,120.0	1335	13,785.0	1033%	7%	9%

Table 4.2: Comparison of production with target and actual & down time level on 2022/2023

The table 4.2 above shows the company registered production time compared with target and down time level for the year 2022/2023. Accordingly the bar chart below clearly shows the productive and non-productive of the overall plant.

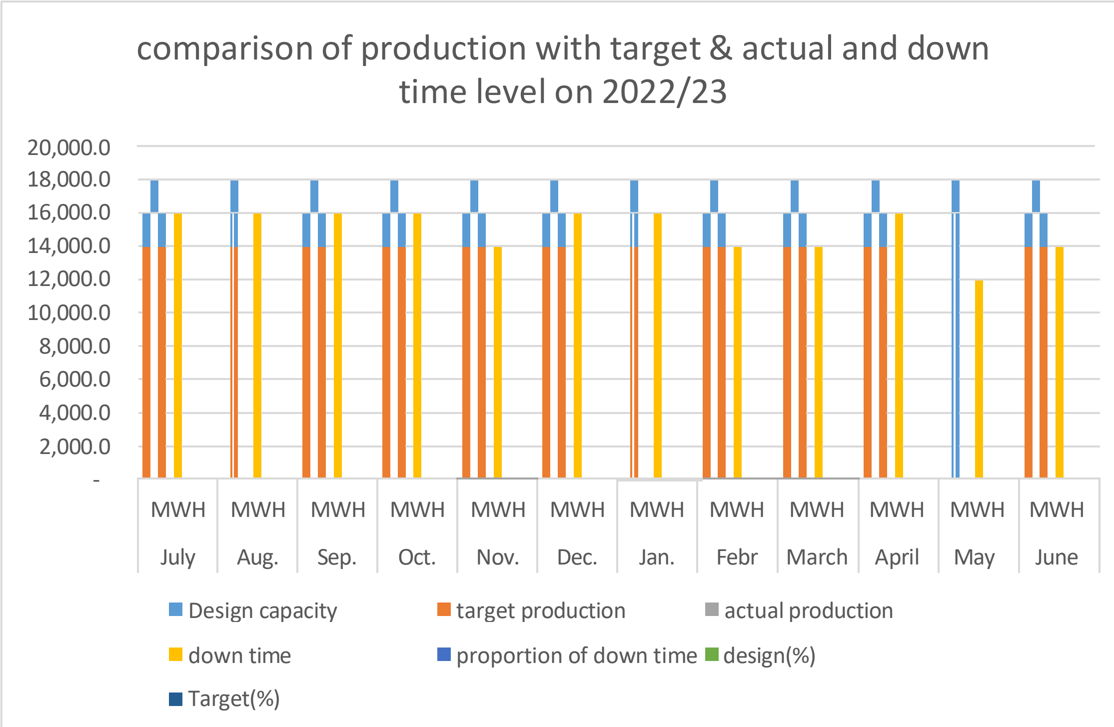

Fig 4.2 comparison of production with target and actual and down time level on 2022/23

As per the figure 4.2 above the actual and down time percent of the company one year was clearly stated, in this section for half of the year the actual production is 0. Therefore, the above analysis shows that the actual average production of the year was less than 10%.

4.4 The current lean maintenance tools practices status & identified areas for improvement

To study the existing situation of the company regarding to the lean maintenance tools application and performance, data was collected and analyzed using table.

Total Productive Maintenance (TPM)

In this survey, as shown in the figure 4.3 that nearly 46 % (15.6%, 15.6%, and 12.5%) of the company's respondents were believe that TPM tools are not practiced in the company properly. in addition to that, 59.4% of the respondents were not agreed as the company is empowering the operators to participant on day to day routine maintenance work.

This implies that in the case company the current TPM application is not as per the requirement.

Total Productive Maintenance		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
TPM is practiced in your WTE power plant	Fi	5	5	4	16	2
	%	15.6%	15.6%	12.5%	50.0%	6.3%
All TPM tools and techniques have been implemented in your WTE power plant	Fi	5	6	10	11	
	%	15.6%	18.8%	31.3%	34.4%	0.0%
Your company empowering operators to perform routine maintenance tasks on their equipment to prevent breakdowns	Fi	4	7	8	13	
	%	12.5%	21.9%	25.0%	40.6%	0.0%
you have observed improvements in equipment performance and reliability since implementing TPM	Fi		2	6	20	4
	%	0.0%	6.3%	18.8%	62.5%	12.5%
Your plant ensuring equipment is capable of producing quality products by addressing defects	Fi	6	8	8	10	
	%	18.8%	25.0%	25.0%	31.3%	0.0%
Continuous improvement activities focused on optimizing equipment performance & eliminating waste is performed in RWTE	Fi	5	9	5	12	1
	%	15.6%	28.1%	15.6%	37.5%	3.1%
the sustainability of TPM practices was ensured in your WTE power plant	Fi	4	9	8	11	
	%	12.5%	28.1%	25.0%	34.4%	0.0%

Table 4.3: Frequency table for TPM

5S practicing

This section describes the current practicing of 5S in the case company. Majority of the respondents 56.9% (65.6%, 43.8%, 31.3%, 43.8%, 56.3, 43.8%, 46.9%) agreed on the practicing of 5S in the case company. on the other hand, nearly 69% of the respondents were not believe that eliminating of unnecessary items or maintenance practice has been not practiced on work place on regular basis. as a result improvements were not constantly observed.

(5S)		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
You are familiar with lean 5S methodology	Fi	1	4	3	21	3
	%	3.1%	12.5%	9.4%	65.6%	9.4%
you have previously implemented 5S Lean principles in your workplace	Fi	2	9	7	14	
	%	6.3%	28.1%	21.9%	43.8%	0.0%
Your power plant is assessing and eliminating unnecessary items from work place on regular basis.	Fi	4	7	11	10	
	%	12.5%	21.9%	34.4%	31.3%	0.0%

All 5S tools have been implemented in your power plant (sort, Set in order, shine, standardize & sustain}	Fi	2	8	8	14	
	%	6.3%	25.0%	25.0%	43.8%	0.0%
you have faced challenges during the implementation of 5S	Fi		3	6	18	5
	%	0.0%	9.4%	18.8%	56.3%	15.6%
You have observed improvements since the implementation of 5S	Fi		9	9	14	
	%	0.0%	28.1%	28.1%	43.8%	0.0%
There is a sustainability of 5S practices ensured in your WTE power plant	Fi	4	8	5	15	
	%	12.5%	25.0%	15.6%	46.9%	0.0%

Table 4.4: Frequency table for 5S

Root Cause Analysis (RCA)		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
the specific failure events or incidents that have occurred within the company is identified and documented properly	Fi	2	9	7	13	1
	%	6.3%	28.1%	21.9%	40.6%	3.1%
To identify the problem, there is a clearly defined issue or incident that needs to be investigated	Fi	4	8	8	12	
	%	12.5%	25.0%	25.0%	37.5%	0.0%
Different RCA methods and techniques are utilized in your WTE power plant. Example 5 whys	Fi	4	8	9	10	1
	%	12.5%	25.0%	28.1%	31.3%	3.1%
There is Lack of expertise in RCA methodologies - Difficulty in accessing relevant data - Time constraints and other	Fi		6	15	11	
	%	0.0%	18.8%	46.9%	34.4%	0.0%
You have observed improvements in identifying and addressing root causes of issues since implementing RCA	Fi	4	8	8	11	1
	%	12.5%	25.0%	25.0%	34.4%	3.1%
There is the method of analyze the data & evidence to determine which of the potential causes are contributed to the problem	Fi	3	7	8	13	1
	%	9.4%	21.9%	25.0%	40.6%	3.1%
There is sustainability of Root Cause Analysis ensured in your power plant	Fi	5	9	6	12	
	%	15.6%	28.1%	18.8%	37.5%	0.0%

Table 4.5: Frequency table for RCA

OEE Practicing

This section describes the overall equipment effectiveness practicing in the case company. Majority of the respondents 43.8% and 12.5% were agreed and strongly agreed on failure analysis conducted in the company. Whereas, nearly 70 % of the respondents believe that the sustainability of OEE monitoring not ensured in the plant facility.

OEE		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
The percentage of time that the equipment is available for production is calculated in your organization (failure analysis)	Fi		6	8	14	4
	%	0.0%	18.8%	25.0%	43.8%	12.5%
The percentage of good quality of the equipment is compared to the total output of energy production on regular bases	Fi	5	9	6	10	2
	%	15.6%	28.1%	18.8%	31.3%	6.3%
the speed or rate at which equipment operates compared to its designed or optimal capacity (Performance)	Fi		7	5	16	4
	%	0.0%	21.9%	15.6%	50.0%	12.5%
The sustainability of OEE monitoring ensured in your WTE power plant	Fi	5	11	6	10	
	%	15.6%	34.4%	18.8%	31.3%	0.0%
OEE serves as a general and inclusive measurement of how will a company's manufacturing operation are performing well	Fi		3	5	20	4
	%	0.0%	9.4%	15.6%	62.5%	12.5%
overall improvements in operational efficiency, cost-effectiveness, and competitiveness are analyzed in your WTE	Fi	4	8	4	13	3
	%	12.5%	25.0%	12.5%	40.6%	9.4%

Table 4.6: Frequency table for OEE

Kaizen practicing

This section describes the current kaizen practicing in the case company. Only 37.5% were agreed on as kaizen was practiced in the case company. Whereas, more than 60% of the respondents were believes that the kaizen is not implemented properly in the case company. The indicator of this initiatives are frequent equipment down time and unplanned production loss.

Kaizen		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
Kaizen is practiced in your organization	Fi	2	11	6	12	1
	%	6.3%	34.4%	18.8%	37.5%	3.1%
All Kaizen initiatives like equipment modifications are implemented in your WTE power plant	Fi	1	8	7	14	2
	%	3.1%	25.0%	21.9%	43.8%	6.3%
There is a focused improvement projects aimed at solving specific issue	Fi	2	8	6	16	
	%	6.3%	25.0%	18.8%	50.0%	0.0%
Small groups of employees who meet regularly to identify & solve work-centered problems	Fi	3	10	7	11	1
	%	9.4%	31.3%	21.9%	34.4%	3.1%
You have encountered challenges in implementing and sustaining Kaizen practices Example resistance to change	Fi	3	7	2	20	
	%	9.4%	21.9%	6.3%	62.5%	0.0%
you have observed improvements in operational efficiency and performance as a result of Kaizen initiatives	Fi	3	10	4	15	
	%	9.4%	31.3%	12.5%	46.9%	0.0%

Table 4.7: Frequency table for Kaizen

Kanban

To describe the current situation of the company regarding to the Kanban system was as indicated in table 4.8 below. Majority of the respondents 56.3% and 21.9% (agreed and strongly agreed) as Kanban is currently utilized in the company. On the other hand, more than 80% of the respondents believed that there is no regular training and education to sustain Kanban. Therefore, there is a limitation of an encouraging communication & collaboration among team members to prioritize tasks.

Kanban		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
Kanban is utilized in your WTE power plant for managing maintenance workflow	Fi		3	4	18	7
	%	0.0%	9.4%	12.5%	56.3%	21.9%
There is a physical or digital cards that represent work items or maintenance tasks	Fi	2	4	3	17	6
	%	6.3%	12.5%	9.4%	53.1%	18.8%
There is an iterative enhancement of the Kanban system	Fi	1	3	8	17	3
	%	3.1%	9.4%	25.0%	53.1%	9.4%

you have observed improvements in workflow management and efficiency since implementing Kanban	Fi		3	12	15	2
	%	0.0%	9.4%	37.5%	46.9%	6.3%
you have faced challenges in implementing and utilizing Kanban in your power plant	Fi	4	6	6	15	1
	%	12.5%	18.8%	18.8%	46.9%	3.1%
In your WTE Kanban supports for using of J-I-T inventory system	Fi	3	9	10	8	2
	%	9.4%	28.1%	31.3%	25.0%	6.3%
There is a regular training and education to sustain Kanban	Fi	6	10	10	6	
	%	18.8%	31.3%	31.3%	18.8%	0.0%
There is an encouraging communication & collaboration among team members to prioritize tasks	Fi		8	6	16	2
	%	0.0%	25.0%	18.8%	50.0%	6.3%

Table 4.8: Frequency table for Kanban

Value Stream mapping practicing

To describe the current situation of the company regarding to the VSM system is as indicated in table 4.9 below. Majority of the respondents 53.1% and 3.1% (agreed and strongly) as VSM is currently utilized in the company. On the other hand, almost near to half (46) % of the respondents believed that the current company's VSM is exposed to wastages.

VSM		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
Value Stream Mapping (VSM) is utilized in your WTE power plant	Fi		7	8	17	1
	%	0.0%	21.9%	25.0%	53.1%	3.1%
Distinguish between activities that directly add value to the product & those that do not	Fi	4	8	6	14	
	%	12.5%	25.0%	18.8%	43.8%	0.0%
You have mapped the VSM for maintenance process	Fi	1	10	10	11	
	%	3.1%	31.3%	31.3%	34.4%	0.0%
In your organization the application of VSM minimized maintenance waste	Fi	1	11	7	12	1
	%	3.1%	34.4%	21.9%	37.5%	3.1%
Continuous monitor & evaluation of the performance of the value stream is ensured in your company to further improve efficiency & quality	Fi	2	10	4	15	1
	%	6.3%	31.3%	12.5%	46.9%	3.1%

There is a plan to expand Value Stream Mapping in your power plant	Fi		3	8	20	3
	%	0.0%	9.4%	25.0%	62.5%	9.4%

Table 4.9: Frequency table for VSM

Reliability Centered Maintenance (RCM)

Table 4.10 below indicates that the status of reliability centered maintenance in the company. Majority of the respondents 63% agreed and strongly agree there is a RCM is practiced in the company by considering critical equipment's. Whereas, more than 62% stated that there is no sustainability of RCM practices to optimize maintenance effectiveness.

Reliability Centered Maintenance (RCM)		Strongly Disagree (%)	Disagree (%)	Undecided (%)	Agree (%)	Strongly Agree (%)
The most critical components or equipment are identified to maintain overall reliability and operational efficiency.	Fi		12	3	13	4
	%	0.0%	37.5%	9.4%	40.6%	12.5%
RCM focuses on optimizing maintenance effectiveness	Fi	3	5	4	18	2
	%	9.4%	15.6%	12.5%	56.3%	6.3%
sustainability of RCM practices ensured in your WTE power plant	Fi	2	15	3	10	
	%	6.3%	46.9%	9.4%	31.3%	0.0%
reliability-centered maintenance strategies be effectively implemented to optimize plant operation in your plant	Fi	4	13	3	10	2
	%	12.5%	40.6%	9.4%	31.3%	6.3%
the primary failure modes and failure mechanisms affecting key equipment and components in your WtE plant are analyzed properly	Fi	3	10	6	12	1
	%	9.4%	31.3%	18.8%	37.5%	3.1%
condition monitoring, predictive analytics, and machine learning, be leveraged to anticipate equipment failures and schedule maintenance activities proactively in WtE facility	Fi	5	12	2	12	1
	%	15.6%	37.5%	6.3%	37.5%	3.1%
The optimal spare parts inventory management strategy is applicable in your WtE to minimize downtime	Fi	6	7	6	13	
	%	18.8%	21.9%	18.8%	40.6%	0.0%

Table 4.10: Frequency table for RCM

4.5 Analytic Hierarchy Process (AHP) Analysis

AHP was first proposed and implemented by Saaty as a method of solving socio-economic problem and currently used for solving many organizational problems. AHP requires the decision maker judgements about the relative importance of each criterion and specify a preference for each decision alternative using each alternative criterion.

AS discussed in the previous Session, for the researcher to continue with the data collection, it must be known what data should be considered for the lean tool selection analysis with AHP tools. In the AHP tools used as an input data for this research, the selection criteria are taken from the case company's 2022/23 performance report. Where the criterions are; Availability, efficiency, quality maintenance and maintenance cost. These are selected because of the case company identifies the company's main operational loses are due to above identified criterion tools. And the AHP alternatives are: 5S, TPM, RCA, OEE, Kaizen, Kanban, VSM and RCM. Which were selected by the case company's operation and maintenance managers and both electrical & mechanical senior specialists. Based on their opinion the group has identified the above eight tools to be considered as an alternative Lean tools

The considered alternatives from the focus group discussion the lost operational availability are; OEE, RCA, RCM and Kanban, operational & basic sustenance problems.

Efficiency: this problem considers the lost time due to the loss of considering TPM, 5S and Kaizen

Quality Maintenance: these are issues arising from no executing preventive works & problems not fulfilling VSM, Kanban, RCA and TPM.

Maintenance Cost: these are due to unresolved premature failure. The team mainly rises its causes as unresolved failure- RCA, RCM, OEE, Kaizen and VSM.

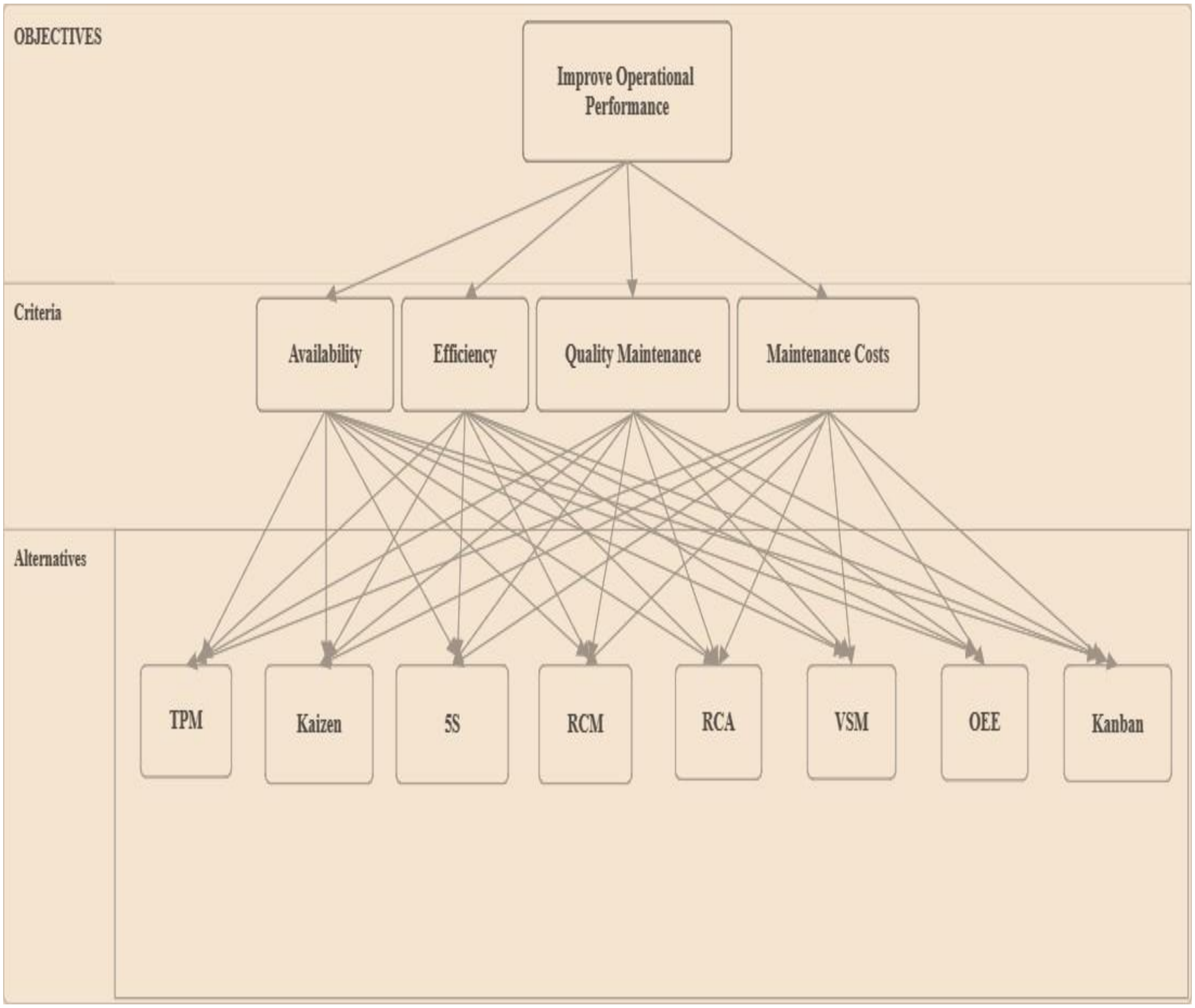

Figure 4.3: AHP Relationships Diagram

The first step in AHP is developing a hierarchical structure as shown on figure 4.3 above. It is put in a descending order from the total objective or the Goal at the top level, the various criteria at the second level, and the alternatives on the third. In this study the Goal is put at the top level, the criteria is at the second level and finally the alternatives are put on the lowest or third level.

1. Scale of relative importance

To make the comparison scale between the tools in the hierarchy, the judgements are made in quantitative terms. Instead of simply assigning a comparison score on an arbitrary basis, a specific numerical value is assigned as shown in the table below by the nine point scale

	Scale of relative Importance	
	1	Equal importance
	3	Moderate Importance
	5	Strong Importance
	7	Very Strong Importance
	9	Extreme Importance
	2,4,6,8	Intermediate importance
	1/3,1/5,1/7,1/9	Are used for inverse comparisons

Table 4.11 Scale of relative importance

2. Pairwise comparison

The second step is the pair-wise comparison for criteria based on the Goal. These shows that there is the dependent of one components on the other. The same can be observed for the alternatives. A hierarchy can be considered as a special case of network where the connections are unidirectional considering their respective dependencies.

3. The third step comprises prioritization.

To achieve this, Additive normalization method is used where the element of each column of matrix A are divided by the sum of the column (normalizing the column), add the corresponding row and finally the sum is divided by the number of elements in the row to get the results.

$$a'_{ij} = a_{ij} / \sum_{i=1}^{n} a_{ij}\, , i, j \;= 1,2, \dots , n$$

$$\mathcal{W}_i = (1/n) \sum_{i=1}^{n} a'_{ij}{}', i, j = 1,2, \dots , n$$

4. The last step is the measurement of the consistence of the judgements.

This step is essential as it examines the accuracy of the judgements with respect to each other. The consistency is measured by the use of consistency ratio (C.R). To get this it is mandatory to calculate consistency index (C.I) and Lambda max ($\lambda_{max).}$

The C.I of a nxn matrix is defined by –
C.I= ($\lambda_{max).}$-n/n-1
Where λ_{max} is the maximum Eigen value of the matrix
Thereafter C.R is calculated as-
C.R= C.I/R,I, C,R < 0.1

Where the R.I is a standard random consistency index.

n	1	2	3	4	5	6	7	8
R.I	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41

Table 4.12: consistency index for different matrix

To move forward to set priorities, need to ensure the consistency ratio (C.R) is below 0.1. If CR is 0.1 or higher, it means there is some inconsistency, and will need to re-evaluate the judgements during the pairwise comparison stage.

4.5.1 Criteria Weighting

Criteria weighting in AHP is all about figuring out what's most important when making decisions. Start by listing criteria, then compare them in pairwise to see which one is more significant and by how much. This helps to assign a weight to each criterion, showing its relative importance with respect to the general goal as per the hierarchy.

Step 1: ranking

	Availability	Efficiency	Quality Maintenance	Maintenance cost
Availability	1.000	7.000	5.000	3.000
Efficiency	0.143	1.000	2.000	0.333
Quality Maintenance	0.200	0.500	1.000	0.333
Maintenance cost	0.33	3.0000	3.000	1.000
Sum	1.6761905	11.5000	11	4.6667

Table 4.13: Pairwise comparison matrix of the Operational performance matrices (criteria)

Step 2: Normalized pair-wise comparison of criteria

To normalize the pair-wise comparison matrix:

First Sum each column of the matrix.
And Divide each element by the sum of its column to normalize the matrix.

	Availability	Efficiency	Quality Maintenance	Maintenance cost
Availability	0.5966	0.6087	0.4545	0.6429
Efficiency	0.0852	0.0870	0.1818	0.0714
Quality Maintenance	0.1193	0.0435	0.0909	0.0714
Maintenance cost	0.1989	0.2609	0.2727	0.2143

Table 4.14: Normalized pair-wise comparison

Step 3: the calculated criteria weighted

Average the values in each row of the normalized matrix

	Availability	Efficiency	Quality Maintenance	Maintenance cost	Criteria Weight
Availability	0.5966	0.6087	0.4545	0.6429	0.57567
Efficiency	0.0852	0.0870	0.1818	0.0714	0.10636
Quality Maintenance	0.1193	0.0435	0.0909	0.0714	0.08128
Maintenance cost	0.1989	0.2609	0.2727	0.2143	0.23669

Table 4.15: the calculated criteria weight

Now the weights for each criterion is calculated, the next step is to check how consistent the judgments are. This means calculate the Consistency Ratio to make sure the decision-making process is solid and reliable.

Step 4: checking for consistency

Use the criteria value which is not normalized

Criteria weighted	0.5756723	0.1063576	0.081283526	0.236686547			
	Availability	Efficiency	Quality Maintenance	Maintenance cost	weighted sum values	Criteria Weight	Eigen values
Availability	1	7	5	3	2.4366	0.5756	4.23271
Efficiency	0.1428	1	2	0.3333	0.4300	0.1063	4.04352
Quality Maintenance	0.2000	0.5	1	0.3333	0.3284	0.0812	4.04131
Maintenance cost	0.3333	3	3	1	0.9915	0.2366	4.18909

Table 4.16: To calculate Eigen value and lambda max.

$\lambda_{max.}$ = (4.23271+4.0435+4.04131+4.18909)/4= 4.12665

Consistency Index (CI)= ($\lambda_{max.}$-n)/(n-1) = (4.126657564-4)/(4-1)

CI =0.042219188

Consistency Ratio (CR)= CI/RI =0.042219/0.9=0.046910209

Where, R.I =0.9 for 4x4 matrix

- Since CR which is 0.0469 <0.1 the weights are accepted and can proceed to the next step

Criteria	Weight	Criteria Rank
Availability	0.57567	The most important criterion
Efficiency	0.10636	The third important criterion
Quality Maintenance	0.08128	The least important criterion
Maintenance cost	0.23669	The second important criterion

Table 4.17: the achieved Criteria weight

From the above table 4.17 criteria weight we can see that the most preferable criteria is Availability with the weight of 57.56%. It is better by far from the second criteria, which shows that it is the most important to focus to deal with the current operational performance problems of the company.

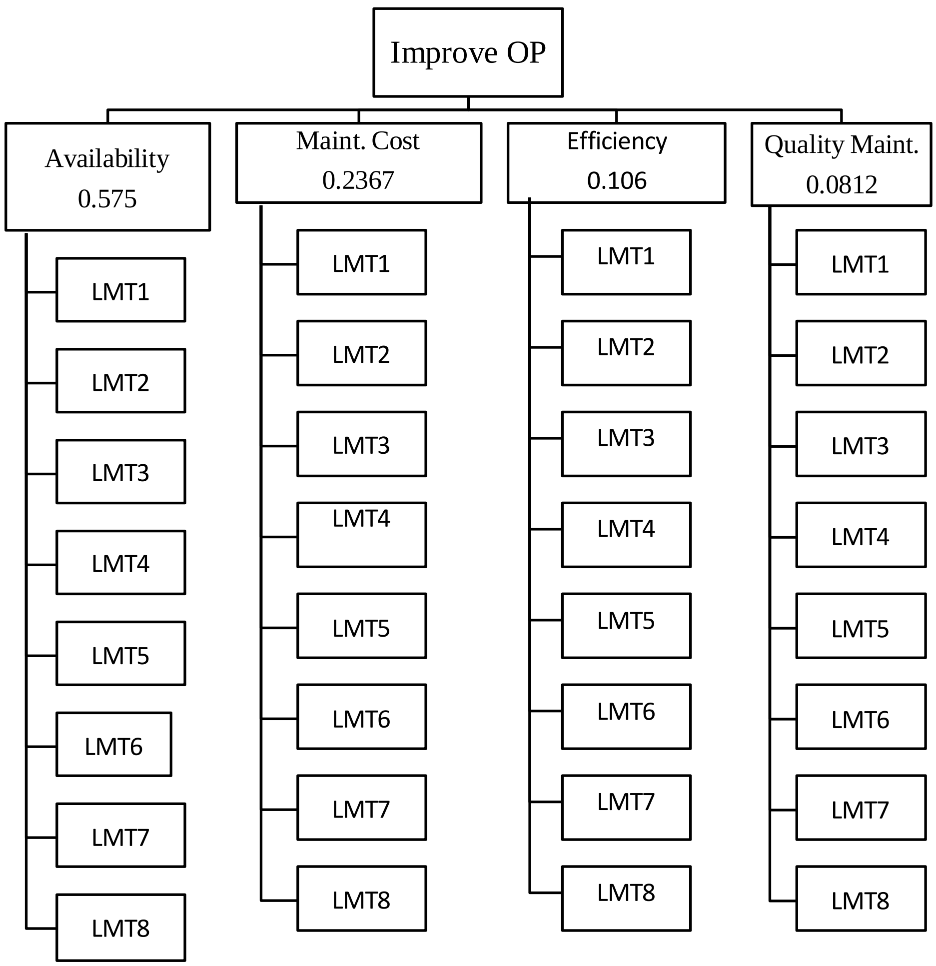

Figure 4.4: Hierarchal tree of OP with criterion weight

4.5.2 Alternative weighting

To determine the preference of each alternative over the other with respect to criterion as stated on the following table

Step 1: pair-wise comparison of alternative matrix

Alternatives	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	1.0000	3.0000	5.0000	7.0000	3.0000	5.0000	7.0000	3.0000
5S	0.3333	1.0000	3.0000	5.0000	0.3333	3.0000	5.0000	0.3333
RCA	0.2000	0.3333	1.0000	3.0000	0.2000	1.0000	3.0000	0.2000
OEE	0.1429	0.2000	0.3333	1.0000	0.1429	0.3333	1.0000	0.1429
Kaizen	0.3333	3.0000	5.0000	7.0000	1.0000	5.0000	7.0000	3.0000
Kanban	0.2000	0.3333	1.0000	3.0000	0.2000	1.0000	3.0000	0.2000
VSM	0.1429	0.2000	0.3333	1.0000	0.1429	0.3333	1.0000	0.1429
RCM	0.3333	3.0000	5.0000	7.0000	1.0000	5.0000	7.0000	1.0000
Sum	2.6857	11.0667	20.6667	34.0000	6.0190	20.6667	34.0000	8.0190

Table 4.18: pair-wise comparison of alternative matrix in terms of Availability

Step 2: Normalized pair-wise comparison of Alternatives

To normalize the pair-wise comparison matrix:

First Sum each column of the matrix.
And Divide each element by the sum of its column to normalize the matrix.

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	0.3723	0.2711	0.2419	0.2059	0.4984	0.2419	0.2059	0.3741
5S	0.1241	0.0904	0.1452	0.1471	0.0554	0.1452	0.1471	0.0416
RCA	0.0745	0.0301	0.0484	0.0882	0.0332	0.0484	0.0882	0.0249
OEE	0.0532	0.0181	0.0161	0.0294	0.0237	0.0161	0.0294	0.0178
Kaizen	0.1241	0.2711	0.2419	0.2059	0.1661	0.2419	0.2059	0.3741
Kanban	0.0745	0.0301	0.0484	0.0882	0.0332	0.0484	0.0882	0.0249
VSM	0.0532	0.0181	0.0161	0.0294	0.0237	0.0161	0.0294	0.0178
RCM	0.1241	0.2711	0.2419	0.2059	0.1661	0.2419	0.2059	0.1247

Table 4.19: Normalized pair-wise comparison of Alternatives

Step 3: the calculated criteria weighted of alternatives

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	Criteria weight
TPM	0.3723	0.2711	0.2419	0.2059	0.4984	0.2419	0.2059	0.3741	0.3014
5S	0.1241	0.0904	0.1452	0.1471	0.0554	0.1452	0.1471	0.0416	0.1120
RCA	0.0745	0.0301	0.0484	0.0882	0.0332	0.0484	0.0882	0.0249	0.0545
OEE	0.0532	0.0181	0.0161	0.0294	0.0237	0.0161	0.0294	0.0178	0.0255
Kaizen	0.1241	0.2711	0.2419	0.2059	0.1661	0.2419	0.2059	0.3741	0.2289
Kanban	0.0745	0.0301	0.0484	0.0882	0.0332	0.0484	0.0882	0.0249	0.0545
VSM	0.0532	0.0181	0.0161	0.0294	0.0237	0.0161	0.0294	0.0178	0.0255
RCM	0.1241	0.2711	0.2419	0.2059	0.1661	0.2419	0.2059	0.1247	0.1977

Table 4.20: Normalized pair-wise comparison of Alternatives with respect to Availability

Now the weights for each alternative or sub criteria is calculated, the next step is to check how consistent the judgments are. This means calculate the Consistency Ratio to make sure the decision-making process is solid and reliable.

Step 4: checking for consistency

Alternatives weighted	0.3014	0.1119	0.0545	0.0254	0.2288	0.0545	0.0254	0.19771			
	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	weighted sum values	Alternative weight	Eigen values
TPM	1.0000	3.0000	5.0000	7.0000	3.0000	5.0000	7.0000	3.0000	2.81900	0.3014	9.35151
5S	0.3333	1.0000	3.0000	5.0000	0.3333	3.0000	5.0000	0.3333	0.93653	0.1120	8.36319
RCA	0.2000	0.3333	1.0000	3.0000	0.2000	1.0000	3.0000	0.2000	0.44486	0.0545	8.16249
OEE	0.1429	0.2000	0.3333	1.0000	0.1429	0.3333	1.0000	0.1429	0.21371	0.0255	8.38512
Kaizen	0.3333	3.0000	5.0000	7.0000	1.0000	5.0000	7.0000	3.0000	2.16026	0.2289	9.43819
Kanban	0.2000	0.3333	1.0000	3.0000	0.2000	1.0000	3.0000	0.2000	0.44486	0.0545	8.16249
VSM	0.1429	0.2000	0.3333	1.0000	0.1429	0.3333	1.0000	0.1429	0.21371	0.0255	8.38512
RCM	0.3333	3.0000	5.0000	7.0000	1.0000	5.0000	7.0000	1.0000	1.76484	0.1977	8.92645

Table 4.21: Calculation of Eigen values for consistency checking for Availability

λmax=8.6468 (the average of Eigen Values column above)

Consistency Index (CI)= ($\lambda_{max.}$-n)/(n-1)

CI = 0.092403

RI for 8x8 matrix is 1.41

Consistency Ratio (CR)= CI/RI =0.092403/1.41= 0.065534

Since CR which is 0.065534 <0.1 the weights are accepted.

Alternative	Weight
TPM	0.3014
5S	0.1120
RCA	0.0545
OEE	0.0255
Kaizen	0.2289
Kanban	0.0545
VSM	0.0255
RCM	0.1977

Table 4.22: the achieved Alternative weight with respect to **availability**

Now, to perform the same calculation for the alternatives with respect to the second criteria of **maintenance cost**; it starts with the pair-wise comparisons gained from the focus groups recommendations.

Step 1: pair-wise comparison of the alternative

OR	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	1.0000	0.2000	0.3333	2.0000	3.0000	5.0000	2.0000	3.0000
5S	5.0000	1.0000	3.0000	7.0000	7.0000	9.0000	4.0000	5.0000
RCA	3.0000	0.3333	1.0000	5.0000	5.0000	6.0000	5.0000	3.0000
OEE	0.5000	0.1429	0.2000	1.0000	1.0000	3.0000	2.0000	2.0000
Kaizen	0.3333	0.1429	0.2000	1.0000	1.0000	2.0000	0.3333	0.3333
Kanban	0.2000	0.1111	0.1429	0.3333	0.5000	1.0000	0.3333	0.5000
VSM	0.5000	0.2500	0.2000	0.5000	3.0000	3.0000	1.0000	2.0000
RCM	0.3333	0.2000	0.3333	0.5000	3.0000	2.0000	0.5000	1.0000
Sum	10.8667	2.3802	5.4095	17.3333	23.5000	31.0000	15.1667	16.8333

Table 4.23: pair-wise comparison of alternative matrix in terms of Maintenance Cost

Step 2: Normalized pair-wise alternatives

To normalize the pair-wise comparison matrix:

First Sum each column of the matrix.
And Divide each element by the sum of its column to normalize the matrix.

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	0.0920	0.0840	0.0616	0.1154	0.1277	0.1613	0.1319	0.1782
5S	0.4601	0.4201	0.5546	0.4038	0.2979	0.2903	0.2637	0.2970
RCA	0.2761	0.1400	0.1849	0.2885	0.2128	0.1935	0.3297	0.1782
OEE	0.0460	0.0600	0.0370	0.0577	0.0426	0.0968	0.1319	0.1188
Kaizen	0.0307	0.0600	0.0370	0.0577	0.0426	0.0645	0.0220	0.0198
Kanban	0.0184	0.0467	0.0264	0.0192	0.0213	0.0323	0.0220	0.0297
VSM	0.0460	0.1050	0.0370	0.0288	0.1277	0.0968	0.0659	0.1188
RCM	0.0307	0.0840	0.0616	0.0288	0.1277	0.0645	0.0330	0.0594

Table 4.24: Normalized pair-wise comparison of alternative matrix in terms of Maintenance Cost

Step 3: calculate the criteria weight for Alternatives

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	Criteria weight
TPM	0.0920	0.0840	0.0616	0.1154	0.1277	0.1613	0.1319	0.1782	0.1190
5S	0.4601	0.4201	0.5546	0.4038	0.2979	0.2903	0.2637	0.2970	0.3735
RCA	0.2761	0.1400	0.1849	0.2885	0.2128	0.1935	0.3297	0.1782	0.2255
OEE	0.0460	0.0600	0.0370	0.0577	0.0426	0.0968	0.1319	0.1188	0.0738
Kaizen	0.0307	0.0600	0.0370	0.0577	0.0426	0.0645	0.0220	0.0198	0.0418
Kanban	0.0184	0.0467	0.0264	0.0192	0.0213	0.0323	0.0220	0.0297	0.0270
VSM	0.0460	0.1050	0.0370	0.0288	0.1277	0.0968	0.0659	0.1188	0.0783
RCM	0.0307	0.0840	0.0616	0.0288	0.1277	0.0645	0.0330	0.0594	0.0612

Table 4.25: calculated criteria weight in terms of Maintenance Cost

Step 4: checking for consistency

Alternative weighted	0.11901	0.37346	0.22546	0.07384	0.04178	0.02699	0.07826	0.06121			
	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	weighted sum values	Alternative weight	Eigen values
TPM	1.0000	0.2000	0.3333	2.0000	3.0000	5.0000	2.0000	3.0000	1.01698	0.1190	8.54520
5S	5.0000	1.0000	3.0000	7.0000	7.0000	9.0000	4.0000	5.0000	3.31621	0.3735	8.87979
RCA	3.0000	0.3333	1.0000	5.0000	5.0000	6.0000	5.0000	3.0000	2.02192	0.2255	8.96818
OEE	0.5000	0.1429	0.2000	1.0000	1.0000	3.0000	2.0000	2.0000	0.63348	0.0738	8.57933
Kaizen	0.3333	0.1429	0.2000	1.0000	1.0000	2.0000	0.3333	0.3333	0.35420	0.0418	8.47859
Kanban	0.2000	0.1111	0.1429	0.3333	0.5000	1.0000	0.3333	0.5000	0.22669	0.0270	8.39823
VSM	0.5000	0.2500	0.2000	0.5000	3.0000	3.0000	1.0000	2.0000	0.64187	0.0783	8.20224
RCM	0.3333	0.2000	0.3333	0.5000	3.0000	2.0000	0.5000	1.0000	0.50609	0.0612	8.26744

Table 4.26: calculated Eigen value to get lambda max for consistency checking in terms of Maintenance cost

λmax= 8.5398745

Consistency Index (CI)= ($\lambda_{max.}$-n)/(n-1)

CI = 0.0771249

RI for 8x8 matrix is 1.41

Consistency Ratio (CR)= CI/RI =0.0771249/1.41= 0.0546985

Since the consistency result is less than 0.1 which is can be proceeded with the gained priority weights for the alternatives with respect to **maintenance costs**.

Alternative	Criterion weight
TPM	0.119012
5S	0.373456
RCA	0.225455
OEE	0.073838
Kaizen	0.041776
Kanban	0.026993
VSM	0.078256
RCM	0.061215

Table 4.27: Criterion weight for alternatives in terms of Maintenance Cost

Next, do similar calculation for the alternatives with respect to the third criteria of Efficiency, similar to the above alternatives it starts with the pair-wise comparison gained from the focus group.

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	1.000	0.200	0.333	0.200	0.143	0.250	0.143	0.333
5S	5.000	1.000	0.500	0.333	0.200	0.500	0.200	0.500
RCA	3.000	2.000	1.000	0.500	0.250	2.000	0.333	1.000
OEE	5.000	3.000	2.000	1.000	0.333	3.000	0.333	2.000
Kaizen	7.000	5.000	4.000	3.000	1.000	5.000	3.000	4.000
Kanban	4.000	2.000	0.500	0.333	0.200	1.000	0.333	0.500
VSM	7.000	5.000	3.000	3.000	0.333	3.000	1.000	3.000
RCM	3.000	2.000	1.000	0.500	0.250	2.000	0.333	1.000
sum	35.0000	20.2000	12.3333	8.8667	2.7095	16.7500	5.6762	12.3333

Table 4.28: Pair-wise comparison of LT in terms of Maintenance efficiency

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	0.0286	0.0099	0.0270	0.0226	0.0527	0.0149	0.0252	0.0270
5S	0.1429	0.0495	0.0405	0.0376	0.0738	0.0299	0.0352	0.0405
RCA	0.0857	0.0990	0.0811	0.0564	0.0923	0.1194	0.0587	0.0811
OEE	0.1429	0.1485	0.1622	0.1128	0.1230	0.1791	0.0587	0.1622
Kaizen	0.2000	0.2475	0.3243	0.3383	0.3691	0.2985	0.5285	0.3243
Kanban	0.1143	0.0990	0.0405	0.0376	0.0738	0.0597	0.0587	0.0405
VSM	0.2000	0.2475	0.2432	0.3383	0.1230	0.1791	0.1762	0.2432
RCM	0.0857	0.0990	0.0811	0.0564	0.0923	0.1194	0.0587	0.0811

Table 4.29: Normalized pair-wise alternative Matrix in terms of Efficiency

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	Criteria weight
TPM	0.0286	0.0099	0.0270	0.0226	0.0527	0.0149	0.0252	0.0270	0.0260
5S	0.1429	0.0495	0.0405	0.0376	0.0738	0.0299	0.0352	0.0405	0.0562
RCA	0.0857	0.0990	0.0811	0.0564	0.0923	0.1194	0.0587	0.0811	0.0842
OEE	0.1429	0.1485	0.1622	0.1128	0.1230	0.1791	0.0587	0.1622	0.1362
Kaizen	0.2000	0.2475	0.3243	0.3383	0.3691	0.2985	0.5285	0.3243	0.3288
Kanban	0.1143	0.0990	0.0405	0.0376	0.0738	0.0597	0.0587	0.0405	0.0655
VSM	0.2000	0.2475	0.2432	0.3383	0.1230	0.1791	0.1762	0.2432	0.2188
RCM	0.0857	0.0990	0.0811	0.0564	0.0923	0.1194	0.0587	0.0811	0.0842

Table 4.30: Calculated criteria weight for Alternatives in terms of Efficiency

Alternative weighted	0.0259	0.0562	0.0842	0.1361	0.32883	0.06553	0.2188	0.0842			
	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	weighted sum values	Alternative weight	Eigen values
TPM	1.000	0.200	0.333	0.200	0.143	0.250	0.143	0.333	0.21523	0.0260	8.28195
5S	5.000	1.000	0.500	0.333	0.200	0.500	0.200	0.500	0.45807	0.0562	8.14466
RCA	3.000	2.000	1.000	0.500	0.250	2.000	0.333	1.000	0.71315	0.0842	8.46882
OEE	5.000	3.000	2.000	1.000	0.333	3.000	0.333	2.000	1.15080	0.1362	8.45142
Kaizen	7.000	5.000	4.000	3.000	1.000	5.000	3.000	4.000	2.85825	0.3288	8.69225
Kanban	4.000	2.000	0.500	0.333	0.200	1.000	0.333	0.500	0.55027	0.0655	8.39766
VSM	7.000	5.000	3.000	3.000	0.333	3.000	1.000	3.000	1.90190	0.2188	8.69111
RCM	3.000	2.000	1.000	0.500	0.250	2.000	0.333	1.000	0.71315	0.0842	8.46882

Table 4.31: Checking for consistency by calculating Eigen value

λmax= 8.4496

Consistency Index (CI)= $(\lambda_{max.}$-n)/(n-1)

CI = 0.0642

RI for 8x8 matrix is 1.41

Consistency Ratio (CR)= CI/RI =0.0771249/1.41= 0.0456

Since the consistency result is less than 0.1 which is; can proceed with the gained priority weights for the alternatives with respect to **efficiency**.

Alternative	Criterion weight
TPM	0.0259875
5S	0.0562421
RCA	0.084209
OEE	0.1361663
Kaizen	0.3288273
Kanban	0.0655263
VSM	0.2188324
RCM	0.084209

Table 4.32: Calculated criterion weight for alternatives in terms of Efficiency

Next, do similar calculation for the alternatives with respect to the fourth criteria of Quality Maintenance, similar to the above alternatives it starts with the pair-wise comparison gained from the focus group

OR	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	1.00	0.33	0.33	1.00	0.14	1.00	1.00	3.00
5S	3.00	1.00	1.00	0.33	0.14	0.33	0.33	3.00
RCA	3.00	1.00	1.00	0.33	0.14	0.33	0.33	3.00
OEE	1.00	3.00	3.00	1.00	0.33	1.00	1.00	3.00
Kaizen	7.00	7.00	7.00	3.00	1.00	5.00	3.00	7.00
Kanban	1.00	3.00	3.00	1.00	0.20	1.00	1.00	5.00
VSM	1.00	3.00	3.00	1.00	0.33	1.00	1.00	5.00
RCM	0.33	0.33	0.33	0.33	0.14	0.20	0.20	1.00
sum	17.3333	18.6667	18.6667	8.0000	2.4381	9.8667	7.8667	30.0000

Table 4.33: Pair-wise comparison of LT alternatives in terms of Quality Maintenance

To normalize the pair-wise comparison matrix:

First Sum each column of the matrix.
And Divide each element by the sum of its column to normalize the matrix.

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM
TPM	0.0577	0.0179	0.0179	0.1250	0.0586	0.1014	0.1271	0.1000
5S	0.1731	0.0536	0.0536	0.0417	0.0586	0.0338	0.0424	0.1000
RCA	0.1731	0.0536	0.0536	0.0417	0.0586	0.0338	0.0424	0.1000
OEE	0.0577	0.1607	0.1607	0.1250	0.1367	0.1014	0.1271	0.1000
Kaizen	0.4038	0.3750	0.3750	0.3750	0.4102	0.5068	0.3814	0.2333
Kanban	0.0577	0.1607	0.1607	0.1250	0.0820	0.1014	0.1271	0.1667
VSM	0.0577	0.1607	0.1607	0.1250	0.1367	0.1014	0.1271	0.1667
RCM	0.0192	0.0179	0.0179	0.0417	0.0586	0.0203	0.0254	0.0333

Table 4.34: Normalized pair-wise comparison of LT alternatives matrix in terms of Quality Maintenance

Average the values in each row of the normalized matrix.

	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	Criteria weight
TPM	0.0577	0.0179	0.0179	0.1250	0.0586	0.1014	0.1271	0.1000	0.0757
5S	0.1731	0.0536	0.0536	0.0417	0.0586	0.0338	0.0424	0.1000	0.0696
RCA	0.1731	0.0536	0.0536	0.0417	0.0586	0.0338	0.0424	0.1000	0.0696
OEE	0.0577	0.1607	0.1607	0.1250	0.1367	0.1014	0.1271	0.1000	0.1212
Kaizen	0.4038	0.3750	0.3750	0.3750	0.4102	0.5068	0.3814	0.2333	0.3826
Kanban	0.0577	0.1607	0.1607	0.1250	0.0820	0.1014	0.1271	0.1667	0.1227
VSM	0.0577	0.1607	0.1607	0.1250	0.1367	0.1014	0.1271	0.1667	0.1295
RCM	0.0192	0.0179	0.0179	0.0417	0.0586	0.0203	0.0254	0.0333	0.0293

Table 4.35: Calculated the criteria weight for Alternatives in terms of Quality maintenance

Alternative weighted	0.07568	0.0696	0.0696	0.1212	0.3826	0.1227	0.1295	0.0293			
	TPM	5S	RCA	OEE	Kaizen	Kanban	VSM	RCM	weighted sum values	Alternative weight	Eigen values
TPM	1.00	0.33	0.33	1.00	0.14	1.00	1.00	3.00	0.63788	0.0757	8.42823
5S	3.00	1.00	1.00	0.33	0.14	0.33	0.33	3.00	0.63314	0.0696	9.09950
RCA	3.00	1.00	1.00	0.33	0.14	0.33	0.33	3.00	0.63314	0.0696	9.09950
OEE	1.00	3.00	3.00	1.00	0.33	1.00	1.00	3.00	1.08184	0.1212	8.92874
Kaizen	7.00	7.00	7.00	3.00	1.00	5.00	3.00	7.00	3.45670	0.3826	9.03580
Kanban	1.00	3.00	3.00	1.00	0.20	1.00	1.00	5.00	1.08939	0.1227	8.88130
VSM	1.00	3.00	3.00	1.00	0.33	1.00	1.00	5.00	1.14040	0.1295	8.80636
RCM	0.33	0.33	0.33	0.33	0.14	0.20	0.20	1.00	0.24636	0.0293	8.41432

Table 4.36: calculating Eigen value for consistency checking

λmax= 8.8367174

Consistency Index (CI)= ($\lambda_{max.}$-n)/(n-1)

CI = 0.1195311

RI for 8x8 matrix is 1.41

Consistency Ratio (CR)= CI/RI =0.0771249/1.41= 0.0847738

Since the consistency result is less than 0.1 which is can proceed with the gained priority weights for the alternatives with respect to Quality Maintenance.

Alternative	Criterion weight
TPM	0.075684
5S	0.06958
RCA	0.06958
OEE	0.121164
Kaizen	0.382556
Kanban	0.122661
VSM	0.129497
RCM	0.029279

Table 4.37: Calculated Criterion weight for alternatives in terms of Quality Maintenance

To achieve the final alternative priorities, the above alternative calculations with respect to the criteria shall be considered along with the criteria weights calculated in the beginning of the AHP analysis. Therefore, it's proceeded accordingly with the criteria, criteria weights, alternatives, and alternative priorities for each criteria as follows.

4.5.3 AHP Result

Table 4.38 presents an alternative priority against four criteria relevant to maintenance strategies within an operational context. This table plays a critical role in evaluating and prioritizing Lean Maintenance Tools (LMT) based on their effectiveness in improving operational performance metrics. The table assesses different maintenance alternatives against specific criteria, which may include factors such as Availability, cost, efficiency, and quality of maintenance. Each alternative lean tool is ranked based on its perceived effectiveness in addressing the criteria. This ranking helps in decision-making regarding which tools to implement.

	Availability	Efficiency	Quality Maintenance	Maintenance cost
Weight	0.57567	0.10636	0.08128	0.23669
TPM	0.30145	0.02599	0.07568	0.11901
5S	0.11198	0.05624	0.06958	0.37346
RCA	0.05450	0.08421	0.06958	0.22546
OEE	0.02549	0.13617	0.12116	0.07384
Kaizen	0.22889	0.32883	0.38256	0.04178
Kanban	0.05450	0.06553	0.12266	0.02699
VSM	0.02549	0.21883	0.12950	0.07826
RCM	0.19771	0.08421	0.02928	0.06121

Table: 4.38: Alternative Priority against each criteria

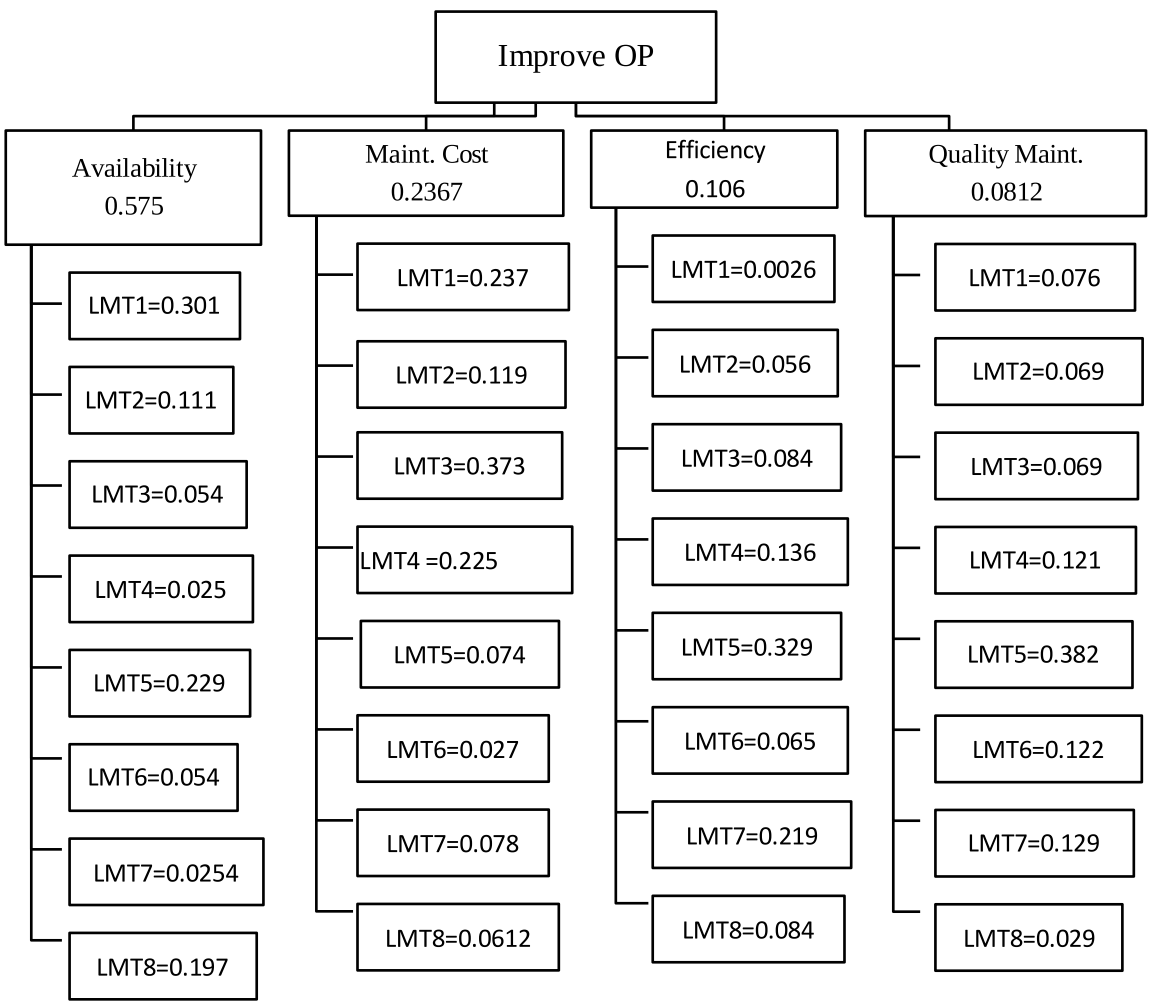

Figure 4.5: By considering the weight of each criterion calculate the alternative priorities

	Availability	Efficiency	Quality Maintenance	Maintenance cost	
Weight	0.57567	0.10636	0.08128	0.23669	Alternative weight
TPM	0.30145	0.02599	0.07568	0.11901	0.210619765
5S	0.11198	0.05624	0.06958	0.37346	0.164494847
RCA	0.05450	0.08421	0.06958	0.22546	0.099348489
OEE	0.02549	0.13617	0.12116	0.07384	0.056479431
Kaizen	0.22889	0.32883	0.38256	0.04178	0.207719526
Kanban	0.05450	0.06553	0.12266	0.02699	0.054702645
VSM	0.02549	0.21883	0.12950	0.07826	0.066994558
RCM	0.19771	0.08421	0.02928	0.06121	0.13964074

Table 4.39: the final combined Alternative priority weight by considering each criteria

The table 4.39 ranks the lean maintenance alternatives based on their calculated priorities, considering various criteria such as quality maintenance, availability, maintenance cost, and operational performance. Each alternative is assigned a numeric weight that represents its priority level, indicating the relative importance of each maintenance strategy in improving operational efficiency.

Alternative	priority
TPM	0.2106198
5S	0.1644948
RCA	0.0993485
OEE	0.0564794
Kaizen	0.2077195
Kanban	0.0547026
VSM	0.0669946
RCM	0.1396407

Table 4.40: Alternative Priority

Alternative	priority	percentage	Rank
TPM	0.2106198	21.06%	1
5S	0.1644948	16.45%	3
RCA	0.0993485	9.93%	5
OEE	0.0564794	5.65%	6
Kaizen	0.2077195	20.77%	2
Kanban	0.0547026	5.47%	8
VSM	0.0669946	6.70%	7
RCM	0.1396407	13.96%	4

From the above table 4.40 alternative weight, we can see that the most preferable lean Maintenance tool for the case company is TPM with the total weight of 21.06%. Which shows that it is the most important tool to deal with the current operational performance problems discussed in the problem section of this research. In the criterion preference seen in the previous section Availability is the first criterion or most important parameter to focus for operational performance improvement. As TPM is directly related to the Availability and proper functioning of the machine that in turns reduce the machine down time, as a result it took more of the relative weight.

Hereafter, based on the above achieved priority, will proceed with the Pareto analysis to consider the data that can serve as the input for model analysis

4.6 Pareto Analysis

The researcher now proceeds to 80/20 rule and identifies the most impactful alternatives that shall be considered in the succeeding step. Here the major alternatives resulting in the main four factor will be pinpointed that will aid in the advance for the model.

Alternative	priority	percentage	cumulative percentage
TPM	0.211	21.1%	21.1%
Kaizen	0.208	20.8%	41.8%
5S	0.164	16.5%	58.3%
RCM	0.140	14.0%	72.2%
RCA	0.099	9.9%	82.2%
VSM	0.056	6.7%	88.9%
OEE	0.067	5.7%	94.5%
Kanban	0.055	5.5%	100.0%
Total	1.000	100%	

Table 4.41: Pareto analysis

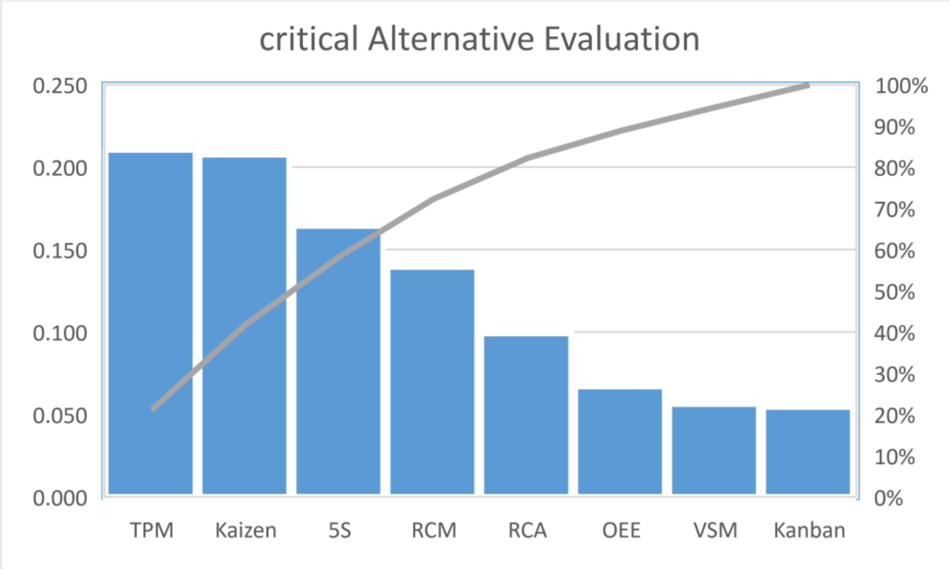

Figure 4.6: Critical Alternative Pareto Evaluation

4.7 Discussion

This study focused only on the case of one company works on RWtE thermal power generation. Therefore, it is not possible to generalize the outcomes to all other power generation plants. The evidence obtained from the survey and secondary data shows that the level of implementation of proper lean maintenance tools is very low. This could have a direct effect on the organizations' performance.

There are different articles discussed on lean and selected those papers from all to discuss mainly lean in health care and manufacturing organizations. Different researchers concluded from those studies lean tool which apply in different industries as per necessity or types of problems are much effective for the finding of waste and improvement of the maintenance process.

Sixty one (61) articles were found after the articles were evaluated. Most of these articles discussed lean in the context of energy generation, food processing, healthcare, aircraft, supply chains, construction, manufacturing, etc. However, there is very little information in the literature about the application of lean maintenance in waste to energy.

The evaluated journals recognized various advantages resulting from the effective use of lean mindset inside their respective organizations. The majority of articles, the researcher saw, highlighted the advantages of lean manufacturing or production; however, there was little discussion of the use of lean maintenance concepts in waste-to-energy power generation.

By removing unnecessary or non-value-added tasks, the lean maintenance approach increases the value of maintenance process activities. By taking into account the operational initiatives of availability, efficiency, quality maintenance, and maintenance costs, this research ultimately improves the case company's operational performance. It also suggests a framework that addresses the application of prioritized lean maintenance tools in RWtE to improve operational performance by minimizing unplanned downtime. The established team then assessed the suggested framework. The framework was created with the goal of enhancing the case company's operational performance, and its validity is confirmed by comparing it with the prior baseline.

4.8 Summary of Finding

Following the researcher's presentation of the study's results and discussion in the preceding section, these are the summaries.

- Operational performance, down time and causes of break down data were analyzed and interpreted on the first section of this chapter and clearly indicates that the current status of the case company. Table 5.1 indicates that the downtime in the fiscal year of 2022/2023 is 80% on average. In addition to that, Table 5.2 indicated that the operational efficiency of RWtE in 2022/2023 fiscal year is only 8.82% this indicates that the company has a challenge to deliver its promises beside low utilization of equipment. The main reason for the down time are related to maintenance issues. Therefore, we can justify applying lean maintenance tools will improve the company’s problems.
- In addition, this section has covered the results and discussion of the survey, its objective to evaluate operational performance improvement using the prioritized lean maintenance tools in RWtE power plant. The reliability and validity of the survey has been confirmed by the triangulation approach. All of the survey respondents were working on different positions in the case company.
- The results of the poll indicate that production employees are not fully involved in carrying out TPM tasks. As per reference [60] the notion that shop floor operators possess the best practical knowledge of the machinery they use on a daily basis underlies the significance of complete employee involvement. This implies that giving operators a sense of ownership over the equipment they use on a regular basis will ensure that it is kept clean and maintained.
- The finding from the survey reveals that there is the shortage of practicing RCA to minimize or eliminate frequent breakdown of critical equipment.

CHAPTER FIVE

5. Proposed Framework Development

5.1 Introduction

Operational performance improvement through lean tool selection for RWtE power plant has been a topic of researcher's interest. This chapter incorporates the proposed framework that is going to be suggested for the case company. According to [53] " the Toyota Way" the main ideas of lean in a form of problem solving model which shows the required steps to be accomplished in finding of the problems and then improve the Operational performances by attacking the root causes; therefore, the proposed framework was derived by using this article as an input.

This chapter is organized according to the sequence of the levels from figure 4.3 above.

AHP Diagram

Based on the results from AHP data analysis and Pareto diagram on figure 4.6 the most preferred lean tools alternatives for the case company for the development of new framework shall be proceeded with the top five alternative tools which accounts for the total weights of 82.2%. It also addresses the results criteria analysis, and used as an inputs for the new framework developments for operational performance improvement.

Rooting on the above analysis the previous prioritized lean tools alternatives; TPM, Kaizen, 5S, RCM and RCA are going to be considered in new operational performance improvement Framework development.

The result from data analysis shows that the main causes of operational loses and machine down times in RWtE is due to mechanical and electrical breakages in Boiler plant as stated in problem statements of this paper.

Improving operational performance in the case company using prioritized lean maintenance tools can lead to significant gain in Availability, Efficiency, Quality Maintenance and reduction of maintenance Costs. Figure 5.2 is the structured framework model selected based on the prioritized lean tools with the potential impact to achieve optimal performance in their operations.

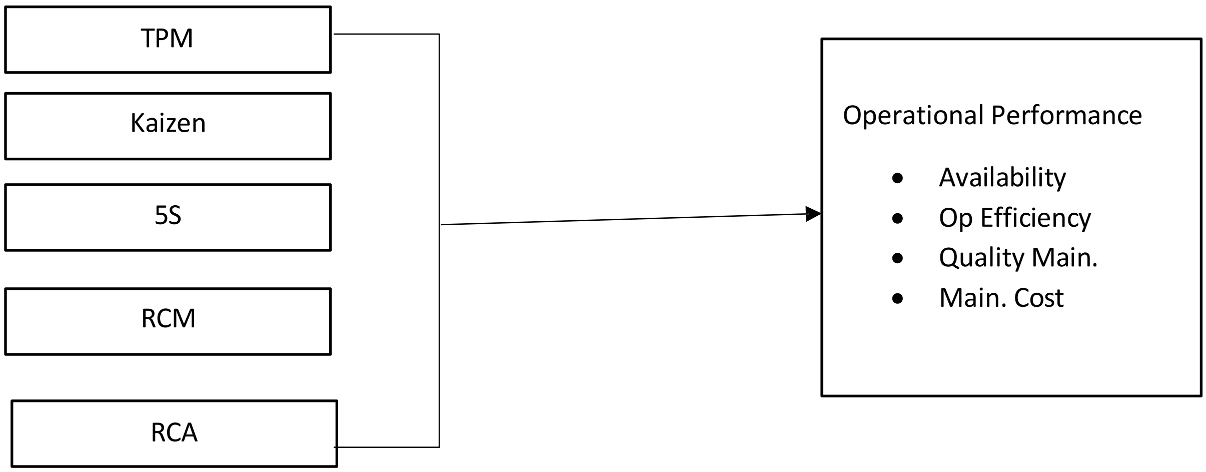

Figure 5.1: the selected lean tools alternatives and criteria for RWtE

5.2 Proposal of selected lean maintenance tools framework

Figure 5.2 presents a framework designed to enhance the operational performance of the Reppie waste-to-energy (WTE) power generation plant. The framework is built on the integration of selected lean maintenance tools that are tailored to address specific operational challenges within the facility. Below are the key components and elements of the proposed framework:

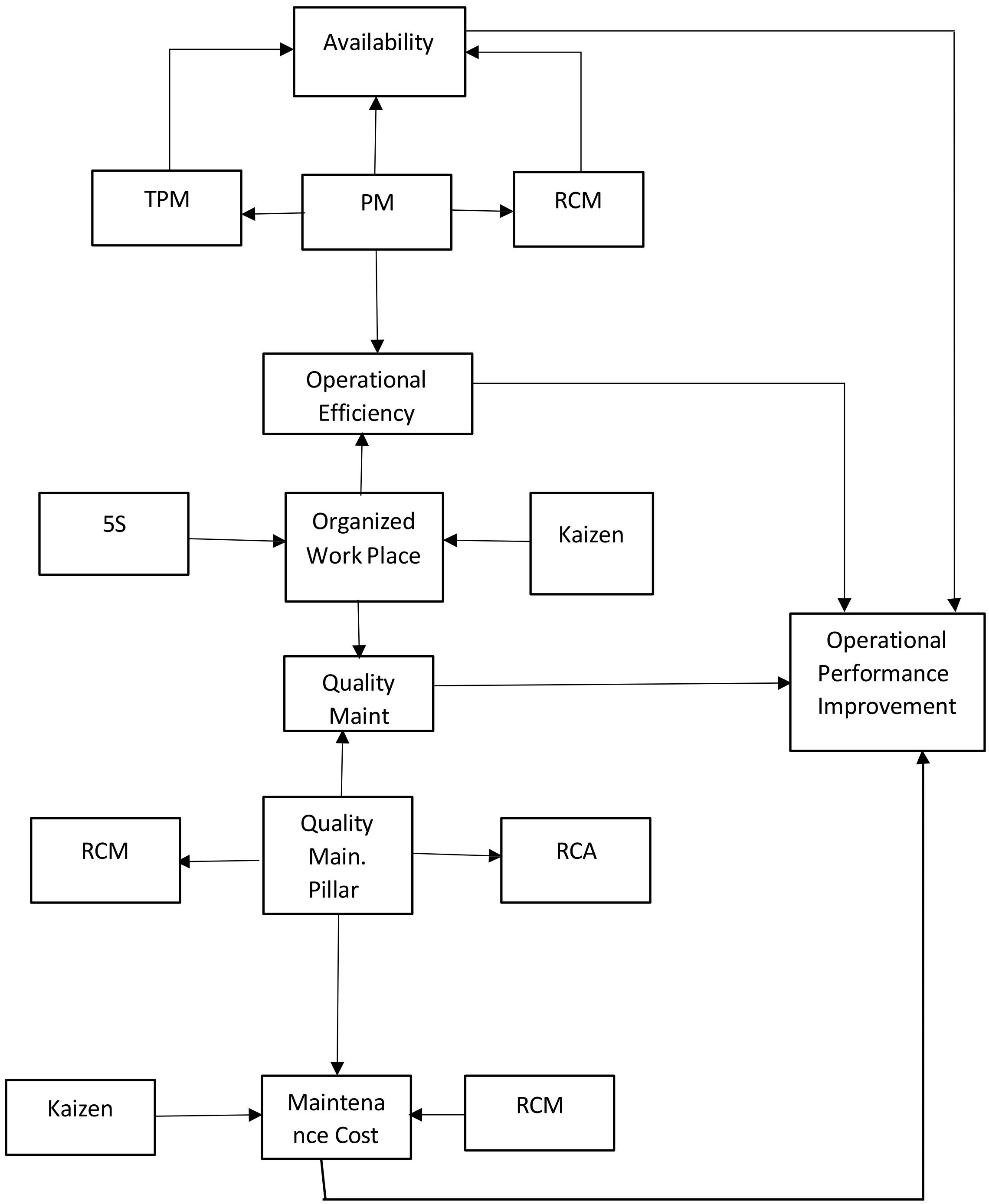

Figure 5.2: the Proposed Framework for the Improvement of the OP in the case company

5.3 Framework Description

In the above figure 5.2 the lean maintenance tools framework has been proposed for the case company. The framework developed based on the selected lean maintenance tools are stated here:

- AS shown on the framework figure above PM, TMP and RCM are used as an input for improvement of availability.
- Kaizen, PM and 5S are used as an input for improvement of operational efficiency
- Organized work place (5S & Kaizen) and Quality maintenance pillars are used as an input an improvement of Quality maintenance
- Kaizen, RCM and quality maintenance pillars are used as an input for improvement (minimization) maintenance costs

1. TPM

Based on the analysis result of the finding as shown on table 4.40, TPM is one of the fundamental elements of lean maintenance tools. It aims to optimize manufacturing machinery availability and efficiency by involving all employees in maintenance. It is a time-based, proactive maintenance that encompasses all organizational levels of operation. TPM manages the production system overall, as well as the shop floor-based system to halt all losses. Elimination of defects, malfunctions, and downtime is one of its objectives.

As stated on the data analysis of figure 4.3 and from the expert opinion The TPM's Essential Components selected from eight pillars of Nakajima (1988) are: Autonomous maintenance, planned maintenance, focused improvements, and Quality maintenance. The result from the interviewers shows that (more than 81%) The four selected pillars have strong association with the improvements of operational improvement of the case company in increase availability, efficiency and reduce maintenance costs.

To this end the actions that have to be done while practicing TPM the pillars based on the case company's current operational problems are presented in figure 5.3 below. Good practicing of Autonomous maintenance pillar which includes the proper involvement of all operation workers in maintenance practicing and work place organization .A proper planned maintenance execution reduces emergency and sudden break down and also reduces safety risks by performing maintenance before damage happened. Focused improvement improve the overall system by performing the standard operation procedure and maintenance procedure. This eliminates unnecessary steps from both operation and maintenance system.

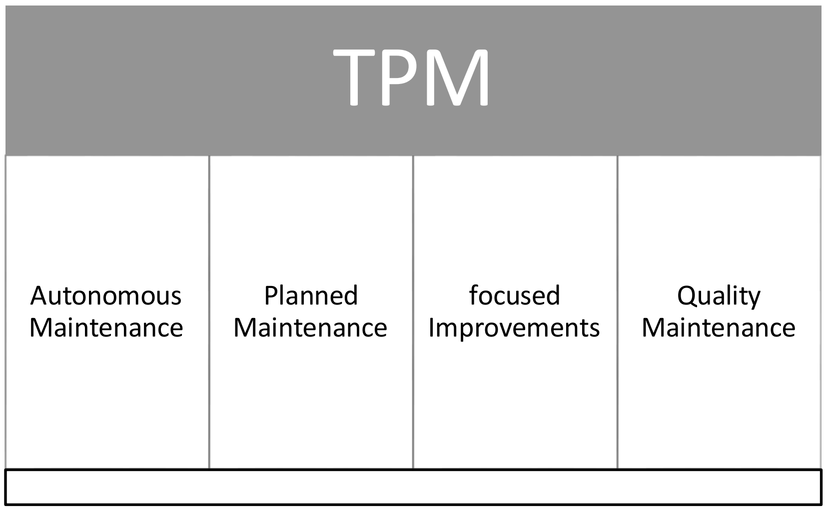

Figure 5.3: Four Selected pillars of TPM implementation

2. **Kaizen**

As shown on the analysis result of this study, kaizen is the second most selected LMT for improving the case company OP. The meaning of the word is "continuous improvement" in Japanese. It’s used to identify wastes or non-value adding activities in maintenance and operations and then eliminates from processes. It's an approach that emphasizes modifying procedures and practices gradually in order to boost effectiveness, output, and general performance. Instead of waiting for big breakthrough, kaizen encourages everyone in an organization to look for little incremental changes to make things better every day. Its main advantage is; improve the availability of equipment’s, improve maintenance procedure and reduces costs related to maintenance. The types of wastes going to be considered to eliminate while implementing kaizen in the proposed framework are: waste in motion, waste in transportation, wastage in over inventory, wastage in waiting, wastage in defect making and waste in over processing.

The actions going to be performed for continuous improvement and elimination focused wastes are:

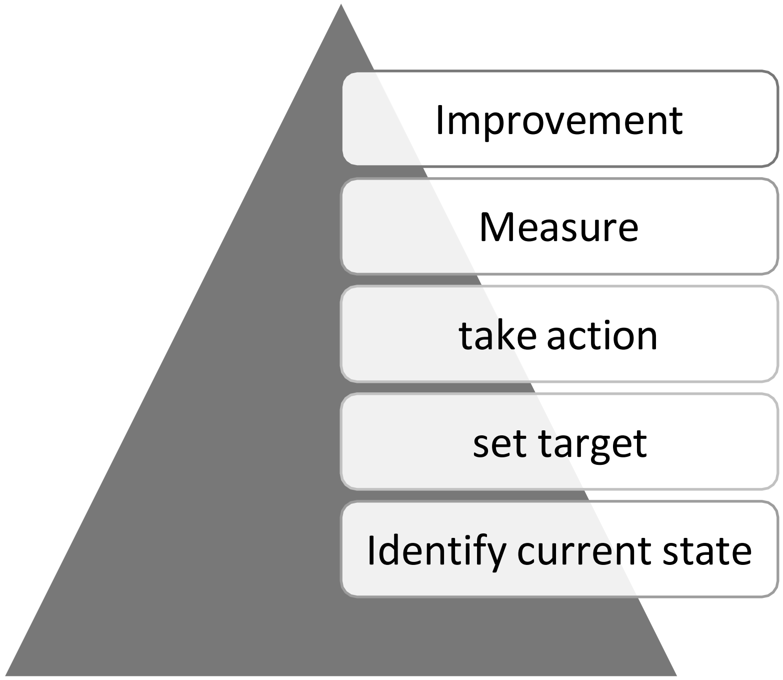

Figure 5.4: Action plan for Kaizen Implementation

3. 5S

The lean maintenance tool includes the five phases of 5S practices, which creates room for a standardized workspace with a focus on waste elimination. The following benefits may accrue to maintenance when 5S is correctly implemented: Increased productivity, efficiency, cleanliness, and safety in the workplace are achieved through the application of 5S approaches in maintenance procedures, which also shorten repair times. The five elements of 5S those should be practiced while implementing 5s on the proposed framework was shown on figure 6.5 below

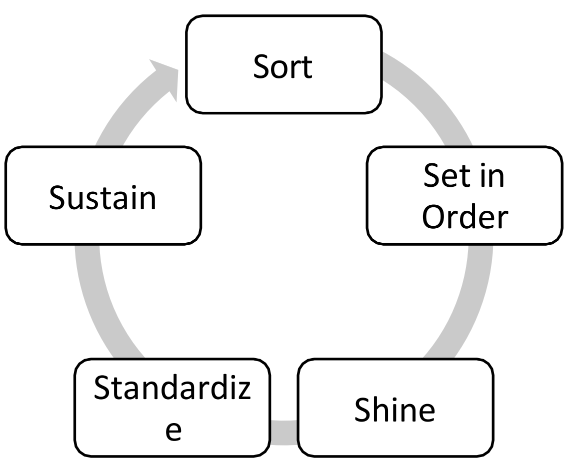

Figure 5.5 5S flow diagram

4. RCM

RCM is the fourth selected lean tools as indicated on the analysis result on table 4.40. It is a methodology employed to ascertain the maintenance needs of physical assets within their current operational context, identifying the various potential failure modes of a component, equipment, or process. It focuses on optimizing maintenance effectiveness and ensure that systems continue to do what their users require in their present operating context.

The goal of RCM, is to maintain the dependability and efficiency of systems and equipment. It all comes down to identifying potential problems, understanding the consequences of those errors, and selecting the most effective preventative measure. RCM places a strong emphasis on preventive maintenance to keep everything in working order rather than just restoring things as they break. By taking the FMEA technique into consideration for RCM improvement, it helps guarantee that equipment operates as intended, limiting downtime and unforeseen surprise failures.

5. RCA

It indicates the various ways that a component, procedure, or piece of equipment failed. It is employed to recognize "event type risks" and their underlying causes, which take the shape of circumstances and behaviors and their interactions. The specific causes are investigated in-depth in order to identify problem solutions that prevent recurrence.

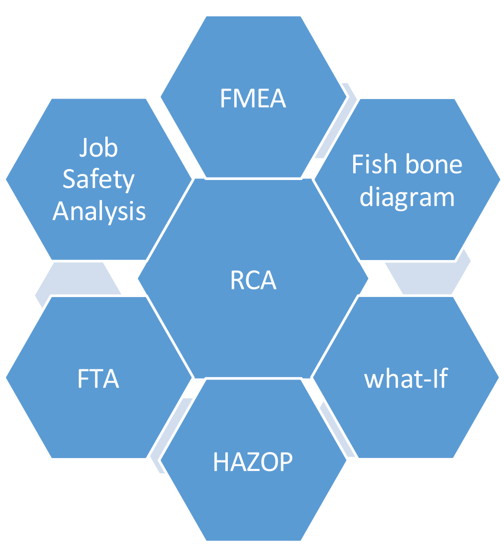

Figure 5.6**:** Elements of RCA going to be considered in implementation framework

5.3.1 Linking of Lean Tools to operational Performance Metrics

1. Availability

Availability is the proportion of time that equipment is operational and available for use, compared to the total time it could be working. Keeping machines available as much as possible is important to get more work done, avoid delays, and everything running smoothly; these are achieved through lean tools **TPM:** Regular and planned maintenance improves machine uptime. And **RCM:** Predictive and preventive maintenance reduce unexpected downtimes.

3 Operational Efficiency

Efficiency means how well a machine performs its job compared to its maximum potential. It's also the ratio of the actual output to the standard output expected. In another words it is about getting the best possible results with the least amount of wasted time, energy, and resources. All these are achieved with the collaboration of lean tools; **5S:** Organized workspaces reduce search time and enhance workflow and **Kaizen:** Continuous process improvements lead to more efficient operations

4 Quality Maintenance

Quality maintenance is keeping machines and equipment in good working condition through regular care, preventing problems, and continuously looking for ways to improve. This ensuring products meet quality standards consistently. The lean tools used to improve quality maintenance are: **TPM:** Quality maintenance pillar focuses on maintaining machine conditions to avoid defects. **Kaizen:** Process improvements often target quality enhancements. **RCM:** Ensuring equipment operates within desired parameters to maintain product quality.

5 Maintenance Costs

Maintenance costs are all the expenses involved in keeping machines and equipment running smoothly and efficiently. These costs include preventive and corrective maintenance, labor, parts, down times and necessary tools and training. To balance these costs lean tools; **TPM:** Reduces reactive maintenance costs through planned and autonomous maintenance. **RCM:** Optimizes maintenance strategies to balance cost and reliability and **Kaizen:** Identifying and eliminating waste in maintenance processes can reduce costs.

5.3.2 Implementation action plan for practicing Developed framework

1. Conduct the current baseline assessment

1.1 To implement the framework, it should start from the operational performance baseline measurement

1.2 Evaluate current maintenance practices (document existing procedures, performance metrics, and areas of inefficiency)

1.3 Gather Data for the KPI (collect data on equipment performance, downtime, failure rates, and maintenance costs

1.4 Analyze the data to identify areas with the highest impact on operational performance

2 Form a lean maintenance team performer (QCC team)

2.1 Form a cross-functional team (members from operations, maintenance, engineering , and management)

2.2 Define roles and responsibilities (endure clear communication and accountability)

3 Give orientation on lean maintenance tools

3.1 Train the team on the selected lean principles (TPM, 5S, Kaizen, RCM VSM)

3.2 Educate on waste identification (give training how to identify and eliminate wastes in maintenance processes)

3.3 Promote a culture of continuous improvement (encourage employees to suggest improvements and in problem-solving activities)

4 Implementation of the Framework

5.4 5S implementation (sort, set in order, shine, standardize, sustain)

5.5 TPM implementation (Autonomous maintenance ,Planned maintenance, focused improvements, Quality maintenance)

5.6 RCM (identify critical equipment, develop maintenance strategies)

5.7 Kaizen Events (conduct regular kaizen events, implement improvements)

5.8 RCA (perform 5 whys,

6 Performance measurement and monitoring

6.3 Metrics such as equipment availability, downtime, MTBF and maintenance costs.

6.4 Monitor progress & identify areas for further improvement.

6.5 Implement visual management (visual aid to display performance)

6.6 Measure (check the actual result with respect to the standardized parameter)

7 Sustainment and seek for further continuous improvement

7.3 Regular audits and Reviews (conduct regular audits, Review & adjust by using check list and other methods)

7.4 Employee engagement (encourage employee involvement, provide ongoing training)

8 cross-collaboration (collaborate with other supportive clients)

9 Periodically analyze data to predict failure and optimize maintenance schedule

By following the above steps the company can develop a lean maintenance frameworks that improves operational efficiency, reduce down time, lowers maintenance costs, ultimately increase the plants overall performance.

5.3.3 Implementation procedure of the proposed framework

Steps 1 to 8 above shows in detail that the sequence that will be followed to implement the proposed framework. Starting from the analysis of the base line for the selected lean maintenance tools to measure the current situation of the company, the implementation of the prioritized lean tools and periodically evaluate the result and set standard so that the indicators and effectiveness of the framework design can be evaluated.

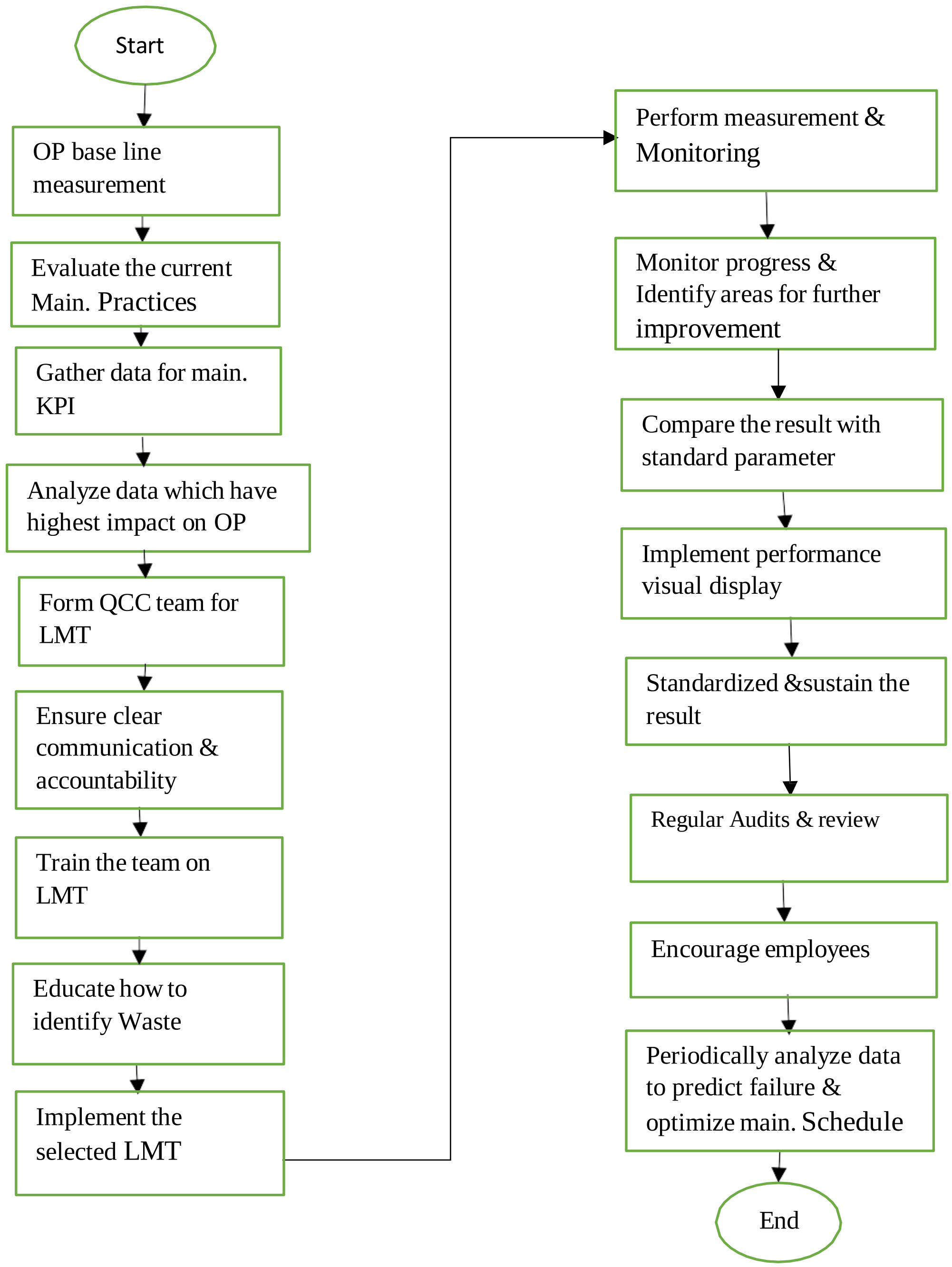

Figure 5.7: General Implementation procedure for the proposed framework

Figure 5.7 illustrates the implementation procedure of the proposed framework to improve the operational performance of the Reppie waste facility. This figure serves as a comprehensive guide describing the steps required to successfully apply lean maintenance tools in the operational environment.

Key elements of the implementation procedure:

1. Assessment of current performance: Assessment of existing operational indicators to identify areas that require improvement.

2. Selection of Lean Maintenance Tools: Select appropriate tools such as Total Productive Maintenance (TPM), 5S, Kaizen, Reliability Centered Maintenance (RCM) and Root Cause Analysis (RCA) based on their potential impact on to operational efficiency.

3. Training and development: Provide the necessary training for staff to effectively use the selected Lean tools.

4. Integration into existing systems: Seamless integration of Lean maintenance tools into current operational practices.

5. Monitoring and evaluation: Establish indicators to evaluate the effectiveness of the tools implemented and their impact on performance.

6. Continuous improvement: Foster a culture of continuous evaluation and improvement of maintenance practices.

7. Stakeholder engagement: Involve all stakeholders in the implementation process to ensure buy-in and cooperation.

8. Documentation and feedback: Keep a complete record of processes and collect feedback to improve the implementation strategy.

Expected results:

• Improved availability: improved uptime of equipment and processes.

• Increased efficiency: Streamlined operations lead to reduced waste and better use of resources.

• Quality maintenance: Higher standards in maintenance practices that ensure equipment reliability and durability.

• Cost reduction: Reduction of operating and maintenance costs through effective maintenance strategies.

The implementation of these procedures, as illustrated in Figure 5.7, is expected to lead to significant gains in operational performance at the RWtE facility, addressing the challenges identified in existing maintenance practices and ultimately contributing to the sustainability and efficiency of the case company's power generation.

To implement the developed framework, the following implementation steps has proposed to be tailed in addition to the above figure.

- The first activity before starting to the implementation process is creating of awareness and this has to be sustained until desired outcome found. [61] Stated that the key factors for lean tool (TPM) implementation are all employee involvement and top managements supports are necessary. Accordingly top management commitment is the basics supports to follow up each activities are exercised as planned in continuous manner.
- Prior to implementation training will be given by the mentors for those who are going apply the framework concerning the application procedure, the route they follow and others issue that helps to make them success full implantation of the method.

5.4 Validation of the proposed framework

Validation is the task of representing that the model is a realistic demonstration of the actual system. The researcher has presented proposed framework considering the selected lean tools that has a positive significant impact in affecting operational performance of the company. Accordingly the proposed model was checked its feasibility by gathering a comment from a chosen expertise opinions to validate the proposed framework.

Accordingly this steps has been followed for validation process

Step 1: Selecting expertise

In this sense, choosing the right expertise for the judgment is essential to have good feedback on this matter. The involvement of a person with strong knowledge and expertise in this field is recommended: Therefore, the plant manager, the maintenance manager, the operation manager, the senior maintenance engineers both mechanical and electrical engineers and the operation shift team were selected for the validation of the framework.

Step 2: preparing interview question

The goal of this feedback is to highlight the proposed framework's significance in operational performance improvement inside the firm. In order to validate the proposed framework, a few interview questions are created to assess the significance of the linked operational performance of the company.

1. Is the proposed framework is useful to the company?
2. Do you believe that this proposed framework is applicable to the case of the case company?
3. Is the framework is clear and understandable to do working on it?
4. How interested would you be working on the proposed framework to improve the operational performance of your company?

Step 3: Conduct Interview

Based on the selected expertise, the researcher has conducted interview with the expertise regarding the proposed framework. The finding found from the expertise interview was that the proposed framework is better to practice and it can solve the current existing problems of the case company’s operational performance problems of the case company; but they strongly mentioned that awareness creation for all employees in each department is mandatory for the successful implementation of the proposed framework. So that, based on the responses, the proposed framework is appropriate for the case company.

CHAPTER SIX

6. Conclusion, recommendation and future work

6.1 Conclusion

Manufacturing companies are constantly looking for adopting the best manufacturing practices to improve their operational performance. The lean principle is a practical approach and low costs of operational performance improvements especially for waste to energy plant. The lean principle system is based on the continuous waste reduction by means of methods not rely on big investments, but on the improvements of act of doing things and performance step by step.

In this research improving operational performance through prioritizing of lean maintenance tools was done for Reppie waste to energy. As discussed in the theoretical background chapter of this paper, higher level of lean maintenance tools implementation results higher operational performance.

According to the RWtE power plant one year data, there is a significant downtime in different plants' section due to wastage of maintenance related activities. As shown from the survey questionnaire result, the problems for low operational performance and reduced machine capacity is mainly due to not practicing proper lean maintenance and not elimination of maintenance related wastes.

Table 4.38 evaluates Lean Maintenance Tools (LMT) based on criteria such as availability, efficiency, quality of maintenance, and maintenance cost. Each tool is ranked to aid decision-making regarding implementation. The analysis reveals that Total Productive Maintenance (TPM) is the most effective tool, addressing operational performance issues primarily related to machine availability. The final rankings emphasize that TPM holds a priority weight of 21.06%, followed by Kaizen (20.78%) and 5S (16.45%). A Pareto analysis identifies these tools as critical to improving operations. The study highlights a low implementation level of lean maintenance tools within the case company, impacting overall performance. It suggests that lean maintenance can enhance operational efficiency by reducing unplanned downtime. The assessment reveals significant downtime and low operational efficiency, indicating a need for better maintenance strategies, particularly the involvement of production employees in maintenance tasks. The findings underscore the benefits of prioritizing and applying lean maintenance frameworks to improve performance in waste-to-energy power generation.

The proposed framework aimed at improving operational performance in a Reppie waste-to-energy (RWtE) power plant, utilizing lean maintenance tools based on principles from "The Toyota Way." Following data analysis via the AHP method and Pareto diagrams, the top five lean tools-Total

Productive Maintenance (TPM), Kaizen, 5S, Reliability Centered Maintenance (RCM), and Root Cause Analysis (RCA)-have been identified for implementation to address operational losses primarily caused by mechanical and electrical failures. The framework focuses on enhancing equipment availability, operational efficiency, quality maintenance, and reducing maintenance costs through strategic application of these tools. Key proposed actions include establishing a baseline performance assessment, forming a lean maintenance team, training employees, and implementing lean practices systematically. Expected outcomes of this framework include increased equipment uptime, improved efficiency, enhanced maintenance quality, and reduced operational costs. Feedback from plant leadership indicates that the framework is relevant and has the potential to solve existing operational challenges the facility faces, suggesting its practical application in the organization.

6.2 Recommendation

The framework which is given as a proposed solution to improve operational performance problems that are discovered throughout the study should be implemented by Reppie Waste to Energy facility so as to improve the selected operational performance metrics.

Based on the results of this research the following recommendations are proposed:

- Operational performance is one of the major factors to win a competition in the global market. Therefore, the company should improve its operational performances continuously and sustainably.
- To solve maintenance related wastes significantly, the company should prioritize and adopt lean tools by using them as a culture of continuous improvement.
- Since implementing all lean tools at a time is very difficult; prioritization should be seriously considered as a very important tool for the company concerning future operational performance improvement.
- Establish clear metrics to track the effectiveness of the company's' maintenance activities and regularly review key performance indicators such as equipment availability, downtime, maintenance costs, and overall efficiency.
- The company should give priority for critical plant section and equipment to minimize implementation interruption.

6.3 Future works

Since this paper has demonstrates only five selected lean maintenance tools to show their contribution towards improving operational performance, future works could focus on the other lean maintenance tools not considered in this study; SMED, TQM, poka-yoke and other tools to show their contribution towards operational improvement.

Besides that, the adaptability of the proposed framework from this study in an actual case study scenario could be conducted in order to view the results first hand and also to improve for further implementation plan.

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Appendix 1

Addis Ababa University

Addis Ababa Institute of Technology (AAIT)

School of Mechanical & Industrial Engineering (SMIE)
(Industrial Engineering Stream)

Questioner on Improving Operational Performance through prioritizing of Lean Maintenance Tools: Reppie Waste to Energy Power Generation Plant

Dear participants;

This questionnaire is designed based on the thesis with title- ***"Improving Operational Performance through Prioritizing Lean Maintenance Tools in RWTE power plant"*** for partial fulfillment of M.SC in mechanical Engineering department (Industrial engineering stream) at AAIT, AAU. With sincerity I would like to extend my deep appreciation to your company and respondents for the willingness and cooperation in undertaking this research. I request your kind cooperation in answering the questions as truthfully as possible. For other questions pertaining to this study, please contact Addis Ababa University, Addis Ababa Institute of Technology, School of Mechanical and Industrial Engineering. The information obtained from this questionnaire will be kept confidential and will not be used for any other purposes.

Part 1: General information

1. Gender: A. Male _________ B. Female __________
2. Age: A 18-30 _____ B. 31-40 ________ C. 41-50 __________D. 50+ _________
3. Current Position or title: _____________
4. Total year of experience: _______________
5. How many years of working experience do you have in this company?

   A. Less than 5 years ☐ B. 5 – 10 years ☐ C. more than 10 years ☐

6. Educational background Level

   A. 10+ 1 ☐ C. 10+3 ☐ E. Degree ☐ G. Others (Specify).........

   B. 10+2 ☐ D. 10+4 ☐ F. Masters ☐

Part II: Lean maintenance tools Dimension

After you read each of the statements, evaluate them in relation to your organization, and then put a tick mark (√) under the choices you prefer your priority.

Where, 1= strongly disagree, 2 = Disagree, 3= Undecided, 4= Agree and 5= strongly agree

1. 5S

LMT1: (5S)	1	2	3	4	5
You are familiar with lean 5S methodology					
you have previously implemented 5S Lean principles in your workplace					
Your power plant is assessing and eliminating unnecessary items from work place on regular basis.					
All 5S tools have been implemented in your power plant (sort, Set in order, shine, standardize & sustain}					
you have faced challenges during the implementation of 5S					
You have observed improvements since the implementation of 5S					
There is a sustainability of 5S practices ensured in your WTE power plant					

2. Total Productive Maintenance (TPM)

LMT 2: TPM	1	2	3	4	5
TPM is practiced in your WTE power plant					
All TPM tools and techniques have been implemented in your WTE power plant					
Your company empowering operators to perform routine maintenance tasks on their equipment to prevent breakdowns					
you have observed improvements in equipment performance and reliability since implementing TPM					
Your plant ensuring equipment is capable of producing quality products by addressing defects					
Continuous improvement activities focused on optimizing equipment performance & eliminating waste is performed in RWTE					
the sustainability of TPM practices was ensured in your WTE power plant					

3. Root Cause Analysis (RCA)

LMT4: RCA	1	2	3	4	5
the specific failure events or incidents that have occurred within the company is identified and documented properly					
To identify the problem, there is a clearly defined issue or incident that needs to be investigated					
Different RCA methods and techniques are utilized in your WTE power plant. Example 5 whys					
There is Lack of expertise in RCA methodologies - Difficulty in accessing relevant data - Time constraints and other					
You have observed improvements in identifying and addressing root causes of issues since implementing RCA					
There is the method of analyze the data & evidence to determine which of the potential causes are contributed to the problem					
There is sustainability of Root Cause Analysis ensured in your power plant					

4. Overall Equipment Effectiveness (OEE)

LMT5 OEE	1	2	3	4	5
The percentage of time that the equipment is available for production is calculated in your organization					
The percentage of good quality of the equipment is compared to the total output of energy production on regular bases					
the speed or rate at which equipment operates compared to its designed or optimal capacity					
The sustainability of OEE monitoring ensured in your WTE power plant					
OEE serves as a general and inclusive measurement of how will a company's manufacturing operation are performing well					
overall improvements in operational efficiency, cost-effectiveness, and competitiveness are analyzed in your WTE					

5. Kaizen

LMT6: Kaizen	1	2	3	4	5

Kaizen is practiced in your organization					
All Kaizen initiatives like equipment modifications are implemented in your WTE power plant					
There is a focused improvement projects aimed at solving specific issue					
Small groups of employees who meet regularly to identify & solve work-centered problems					
You have encountered challenges in implementing and sustaining Kaizen practices Example resistance to change					
you have observed improvements in operational efficiency and performance as a result of Kaizen initiatives					

6. Kanban

LMT7: Kanban	1	2	3	4	5
Kanban is utilized in your WTE power plant for managing maintenance workflow					
There is a physical or digital cards that represent work items or maintenance tasks					
There is an iterative enhancement of the Kanban system					
you have observed improvements in workflow management and efficiency since implementing Kanban					
you have faced challenges in implementing and utilizing Kanban in your power plant					
In your WTE Kanban supports for using of J-I-T inventory system					
There is a regular training and education to sustain Kanban					
There is an encouraging communication & collaboration among team members to prioritize tasks					

7. Value stream Mapping (VSM)

LMT8: VSM	1	2	3	4	5
Value Stream Mapping (VSM) is utilized in your WTE power plant					
Distinguish between activities that directly add value to the product & those that do not					
You have mapped the VSM for maintenance process					
In your organization the application of VSM minimized maintenance waste					

Continuous monitor & evaluation of the performance of the value stream is ensured in your company to further improve efficiency & quality					
There is a plan to expand Value Stream Mapping in your power plant					

8. Reliability centered maintenance (RCM)

LMT8 RCM	1	2	3	4	5
The most critical components or equipment are identified to maintain overall reliability and operational efficiency.					
RCM focuses on optimizing maintenance effectiveness					
sustainability of RCM practices ensured in your WTE power plant					
reliability-centered maintenance strategies be effectively implemented to optimize plant operation					
the primary failure modes and failure mechanisms affecting key equipment and components in WtE plant are analyzed					
condition monitoring, predictive analytics, and machine learning, be leveraged to anticipate equipment failures and schedule maintenance activities proactively in WtE facility					
The optimal spare parts inventory management strategy is applicable in your WtE to minimize downtime					

Part III. Operational Performance Dimensions

1. Availability

OP1: Availability	1	2	3	4	5
Availability is monitored to measure equipment uptime & address downtime issues					
Availability metrics are measured and recorded in your power plant					
Time during which equipment is not operational due to breakdowns & repairs is calculated and noted to the workers					
You have observed improvements in equipment uptime while calculating availability					
Performance and continuous improvement monitoring have conducted to sustain availability					

You have a method which increase the availability of the machine					

2. Operational Efficiency

OP2 : Efficiency	1	2	3	4	5
The efficiency is monitored and utilized in your power plant					
The production focused on maintenance practice					
Stoppage of production has a huge impact on the organization					
There is a frequent machine down time					
Machine downtime reduces designed or planned operation capacity					
In your company unexpected maintenance cost happens highly					

3. Quality Maintenance

OP3 Quality Maintenance	1	2	3	4	5
The maintenance team is good in handling maintenance in professional way					
Working on minimizing and eliminating defect is your concern in day to day activity					
Monitoring and controlling process parameters to ensure consistency is performed properly					
Couse oriented rather than reactive approach is the way you are working in your company					
No customer compliant on quality as a result of poor operation					
There are scraps and quality defects as a result of poor maintenance handling in your company					

4. Maintenance Cost

OP4 Maintenance Cost	1	2	3	4	5
Maintenance Cost (MC) are monitored and analyzed in your WTE power plant					
Components of maintenance costs such as labor and material costs are analyzed properly in the company					

Planned and break down cost is recorded separately and analyzed properly					
Cost for break down and planned maintenance is recorded separately in your organization					
There is a maintenance cost reduction strategy in your power plant					
Regular cost monitoring and analysis is conducted in your power plant					

1. In the time of reduced operational performance which methods used to enhance production capacity?

   ____
   ____
   ____
2. What are the main factors that influencing the operational performance of your organization?

____
____
____

3. How you or your company measures maintenance capacity and performance?

____
____
____

4. What type of maintenance strategy does the company used?
   Preventive _____ Condition based _______ Corrective _________________ other _________
5. What types of operational performance measures does your company considers as a KPI to improve plant's performance?

   ____
   ____
   ____
6. Is your company practicing lean maintenance tools to improve the overall plant availability?
   If yes list the tools that were commonly practiced ________________________________
7. Which TPM pillars do you think are the most important factor for your company? List from the most important to least? ____

   ____