Global Scientific JOURNALS

GSJ: Volume 10, Issue 4, April 2022, Online: ISSN 2320-9186

www.globalscientificjournal.com

Master in Manufacturing Management 2020/2021

Overall Equipment Effectiveness in Sri Lankan Palm Oil Industry: A Case Study of ABZ Company

KDKY Jayatillake

MMM/2020/19

Faculty of Graduate Studies

University of Colombo

February 20

DECLARATION

I certify that this dissertation does not incorporate without acknowledgment any material previously submitted for a Degree or Diploma in any University; and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

(K.D.K.Y. Jayatillake) MMM/2020/19 10/07/2021

Supervisors' Certification

I approve the research thesis titled "Overall Equipment Effectiveness in Sri Lankan Palm Oil Industry: A Case Study of ABZ Company" by K.D.K.Y. Jayatillake, Registration No: MMM/2020/19 for the submission to the Faculty of Graduate Studies, University of Colombo, Sri Lanka, in fulfillment of final requirement of the research thesis for Master in Manufacturing Management.

Signature

Date: 02.06.2021

Professor K. Amirthalingam

Department of Economics,

University of Colombo

ABSTRACT

According to the careful observation of annual reports of ABZ Company, it reveals that maintenance cost of ABZ has been increased gradually over the last few years due to inadequate performance in the process. The main purpose of this research is to find out the reasons for the low performance in ABZ. Performance measurement has a great significance for the top managers in effective decision-making process to evaluate the progress of their predetermined set goals. Therefore, this research which is based on Overall Equipment Effectiveness in Sri Lankan Palm Oil Industry, has highlighted mainly four objectives such as measurement of the Overall Equipment Effectiveness of ABZ Company, identification of the factors affecting Overall Equipment Effectiveness of ABZ Company, comparison of the level of Overall Equipment Effectiveness of ABZ Company with other world standard Palm Oil Mills and finally finding the solutions to improve Overall Equipment Effectiveness of ABZ Company.

All the relevant data to calculate OEE was collected for the last two years. Furthermore, the secondary data of other best world-class Malaysian palm oil mills was also collected by contacting mill managers in Johor, Kedah, Melaka, Pahang, and Sabah. By the calculation of availability, performance, and quality rate, OEE measurement was calculated.

According to the calculation, availability was high from January to April in off-peak months. However, due to mill breakdown, the availability ratio was low during peak season, from May to December. The main reasons were the insufficient capacity of the mill and idle machines in the process because of bottleneck operations.

Minitab 17.0 was used to analyze the calculated results statistically. OEE values were high in January, February, March, and April Months. It reveals that OEE values are high in the off-season period, while the rest of the time they are low due to insufficient capacity in the mill. The quality rate had a mean value of 0.9311 while the availability rate and performance rate had a mean of 0.7963 and 0.7347, respectively. From the analysis, it shows that availability and quality rates are significant in predicting the Overall Equipment Effectiveness, whereas performance is not. The correlation coefficient values of availability rate, performance rate and, quality rate for the effect of OEE with reference to other parameters were 0.979, -0.042, and 0.907, respectively.

ABZ has the lowest availability and performance factors in comparison to other mills. Hence, it should be improved in performance rate in order to enhance the OEE in ABZ. OEE score of

85% is considered world-class for discrete manufacturers. Sterilizer station is the bottleneck of Crude Palm Oil production line in ABZ, which can be eliminated by the addition of another parallel sterilizer. In the kernel oil processing line, kernel heating is the bottleneck which can be eliminated by the addition of another parallel kernel heating tank. In the kernel meal process, by using a new advanced kernel meal bagging technique, the bottleneck can be eliminated. Maintaining good manufacturing practices within the premises, reduction of downtimes of the mill, increasing the capacity and implementing tools like Total Productive Maintenance and Lean, ABZ can enhance their OEE and the productivity.

Keywords: Overall Equipment Effectiveness, Correlation coefficient, Total Productive Maintenance, Lean

ACKNOWLEDGEMENT

I owe my utmost gratitude to my research supervisor, Professor K. Amirthalingam(PhD), Department of Economics, University of Colombo for the immense support, valuable guidance, encouragement and overall insights in this field that have made this an inspiring experience for me. His dynamism, vision, sincerity and motivation have deeply inspired me. Besides my supervisor, I would like to express my deep and sincere gratitude to the Course Coordinator, Professor S.P. Premaratna (PhD, MPhil, MA, BA, DSW), Faculty of Graduate Studies, University of Colombo for giving me the opportunity to do the research and providing invaluable guidance throughout this research.

Furthermore, my sincere thanks go to all the lecturers who taught me the relevant course modules related to Manufacturing Management since my postgraduate level.

I am extremely grateful to Mr. Ruwan Goonawardena, Chief Executive Officer, for providing me this golden opportunity to complete this research in ABZ alongside my day-to-day duties.

The data and the information provided by the research committee members (U.G. Madhushani, G.Y. Sandaruwani, K.L. Manawadu, G.M. Hansika and C.W. Chameeka) were very much useful to me through their work studies, motion studies, and past record analysis in order to complete both the results part and the discussion part based on the results analysis. Hence, I am thankful to them for their support.

Last but not the least, I would like to thank my wife, who supported me in analyzing the results through Minitab 17.0 software, and my lovely parents for supporting me spiritually throughout my life.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

OEE	Overall Equipment Effectiveness
TPM	Total Productive Maintenance
CPO	Crude Palm Oil
CPKO	Crude Palm Kernel Oil
FFB	Fresh Fruit Bunches
PM	Preventive Maintenance
OER	Oil Extraction Rate
KPI	Key Performance Indicators
CBM	Condition Based Maintenance
RCM	Reliability Centered Maintenance

GDP	Gross Domestic Products
ERP	Enterprise Resource Planning
BDM	Breakdown Maintenance
AM	Autonomous Maintenance
MTBF	Mean Time between Failures
MTTR	Mean Time to Repair
TPS	Toyota Production System
IV	Independent Variables
MV	Moderating Variables
DV	Dependent Variables
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Overview of background information

1.1.1 Global palm oil production

Oil palm (*Elaeis guineensis*) cultivation was started in West Africa over 5000 years ago. As a result of the British Industrial Revolution, the international market for palm oil was significantly expanded in South Asia, especially in Malaysia, Indonesia, Thailand and Papua New Guinea. The first commercial scale plantation in Malaysia was founded in 1917 and thereafter, it was established in Tennamaran Estate. (History and Origin, 2014)

Oil palm trees give the highest yield of oil per unit area of cultivated land. 72.27 million metric tons (MT) of palm oil was produced globally in the marketing year of 2019/2020. There is a capability of producing 10 times more oil from one hectare of oil palm plantation with the comparison of other types of oilseed crops. (History and Origin, 2014)

Two distinct types of oils are produced by palm fruit: crude palm oil (CPO) from the mesocarp and crude palm kernel oil (CPKO) from the inside kernel. Both types of oils are used for food-based products as well as non-food based products such as margarine, ice-cream, chocolates, cookies, detergents, soaps, noodles, lubricants, etc.

1.1.2 Sri Lankan palm oil industry

A European planter, M. Jerry Wales who was the pioneer, commenced the cultivation of oil palm in Sri Lanka in 1968 at Nakiyadeniya estate by planting 68 oil palm plants. Oil palm cultivation has rapidly increased throughout Sri Lanka's low country wet zone since 1968, as it was tended as an economical and profitable crop compared to other types of traditional crops. (Palm Oil, 2021)

According to the present research, it can be identified that there are several plantations that cultivate oil palm in Sri Lanka such as Watawala, Agalawatte, Elpitiya, Namunukula, Kotagala and Horana. The palm oil processing mill at Nakiyadeniya, managed by Watawala Plantation PLC, is the largest oil palm mill in Sri Lanka and has 20 MT of Fresh Fruit Bunches (FFB) processing capacity and advanced latest technology. The mill was commissioned in 1980 as a small-scale industry and, in 1992 expanded its capacity to process 15 metric tons of fresh fruit bunches per hour. Nakiyadeniya oil palm mill produces different types of palm oil such as crude palm oil, palm kernel oil, palm kernel cake, R.B.D palm olein, and stearine, etc. (Nakiyadeniya Oil Palm Mill, 2013)

ABZ Palm Oil Processing Pvt. Ltd is a palm oil mill that has a joint venture with Agalawatta Plantation Plc., Elpitya Plantation PLC., and Namunukula Plantation PLC. (Three main suppliers), and processes oil palm of three partners to produce crude palm oil that is traded in the local market. The main products are Crude Palm Oil (CPO), Crude Palm Kernel Oil (CPKO) and Kernel Meal (KM) which is the only by-product. ABZ factory has a processing capacity of 12 metric tons of fresh fruit bunches per hour. Nakiyadeniya Palm Oil Factory, which belongs to the Watawala Plantation PLC, is the sole competitor. Final CPO and CPKO customers are Sena mills, Pyramid Lanka, NMK and Unilever.

1.1.3 ABZ palm oil manufacturing process

In the conventional crude palm oil extraction process, fresh fruit bunches (FFB) are cooked during sterilization using saturated steam at a pressure of 3 bar in horizontal, vertical, or tilting sterilizers. Bunches are sterilized for the purpose of facilitating mechanical separation, rupture of the oil cells, inactivating oil-splitting enzymes, preserving the kernel and coagulating protein material. (Wai-Lin, 2021)

Then sterilized fruit bunches are stripped to separate the sterilized fruits from the empty fruit bunches while the empty bunches are pressed in empty bunch press machines. The sterilized stripped fruits are then reheated and agitated in digesters where live steam is supplied for the purpose of loosening the mesocarp from the nuts in preparation of a homogenous pulp for pressing. The screw press squeezes out a liquor called press liquor, consisting mainly of palm oil, water and solid debris from the press cake, consisting of fiber and nuts. The heavy and coarse fibrous solid particles in the press liquor are then removed from the vibrator screens. The palm oil is separated from the water and solids by the theory of density difference in the process of clarification. (Wai-Lin, 2021)

The oil layer in the clarification tank is transferred to a pure oil tank where impurities are drained. Following that, crude palm oil is sent through the vacuum dryer to lower the moisture content of the crude palm oil below 0.20% before being sent to the storage tank. In the conventional clarification process, the primary separation is achieved in continuous settling tanks using gravity. The press liquor from the screw press is pumped to the clarification tanks using centrifugal pumps. For optimum separation, it is necessary to maintain three main parameters: settling time, dilution with water, and settling temperature. (Oil room,2015)

Underflow sludge from the clarification tank has approximately 10% oil, the bulk of which can be recovered using a sludge centrifuge after de-sanding hydro-cyclone, leaving substantially de-oiled clarification process effluent. Due to centrifugal force, the heavier particles of dirt and water are forced to the extreme end of the rotor while the lighter oil particles are centered in the bowl. (Sivasothy & Ramachandran, 2010)

The oil recovered by the sludge centrifuge contains some water and dirt and is therefore returned and recycled to the clarification tank for further oil settlement. Two types of sludge centrifuges are currently used in mills. The stack disk centrifuge can handle a much larger capacity, and its operation is quite easily automated. The other centrifuge uses a star-shaped rotating bowl. In spite of its smaller capacity, this centrifuge is still popular because of its lower capital and maintenance costs. Three-phase decanters are used to reduce the quantity of effluent where slurry is separated into oil, water, and solid cake phases. (Sivasothy & Ramachandran, 2010)

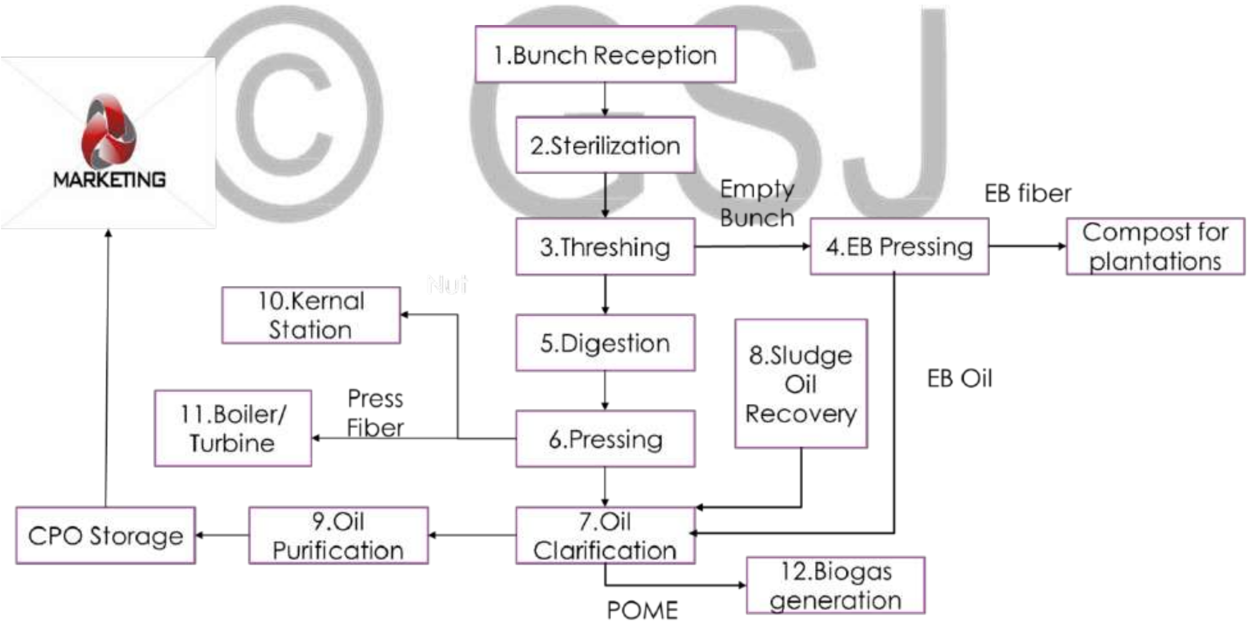

Figure 1.1: Process flow chart

Palm oil manufacturing factories are one of the most complex plants among other manufacturing firms as they consist of a lot of huge machines and equipment that must be maintained in good working condition. To ensure continuous operation and achieve the desired throughput, a proper preventive maintenance system is needed in the palm oil mill. It is a unique place that utilizes a lot of resources for improving maintenance management processes. Effective preventive maintenance (PM), condition monitoring, inspection, and troubleshooting techniques are used in palm oil mills around the world on various kinds of components, including pumps, motors, gears, bearings, chain, pipes, valves, couplings, seals, fans, lubrications, lifting equipment, hydraulics, pneumatics, compressors, steam, electrical systems, etc. (Naim, 2009)

PM techniques such as condition monitoring, lubrication, alignment, cleaning, and other preventive maintenance systems should be done at the right time in order to run the process continuously. However, all of those maintenance activities are based on the crop schedule, crop availability, and other external factors. Sometimes the entire process is shut down due to plant maintenance due to boiler break-down, sterilizer break-down, etc. (Ismail et al., 2009)

Even though a few initiatives such as steam energy saving initiatives, sustainable manufacturing systems (effluent treatment projects), and new oil settling projects, etc. have been taken to maintain the standard of the company, there is no mechanism to measure the performance of the mill. In the current scenario, ABZ focuses only on oil extraction rate (OER), which means how much oil is extracted from the processed crop. It provides information only on the efficiency of oil recovery. However, the process has to run without any delay, with optimum conditions and optimum quality in order to achieve the set goals.

In order to be competitive with importing palm oil from other countries, it is essential to increase the maintenance management performance of palm oil processing. Poor maintenance management of the mill equipment can affect the competitiveness of the organization by reducing throughput, increasing losses, and leading to poor effectiveness. Performance cannot be achieved successfully without measurement, which provides the necessary information to management for effective decision-making and is used by the industry to assess progress against set goals and objectives by means of measurements for effectiveness and efficiency. (Baluch, Abdullah & Mohtar, 2010).

1.2 Research problems

Particular research study have not been conducted in the field of “Overall Equipment Effectiveness in Sri Lankan Palm Oil Mills”.

According to the careful observation of annual reports of ABZ Company, it is revealed that the maintenance cost of ABZ has been increased gradually over the last few years due to inadequate performance in the process. Since there is no proper mechanism to evaluate its performance, the mill's management has been frustrated for many years from the time of its beginning. Not only local literature but also international literature, including Malaysian Palm Oil
Journals, shows that particular research has not been done in the field of “Overall Equipment Effectiveness Evaluation in Palm Oil Mills in the Sri Lankan context”. It is imperative that palm oil mills recognize the Overall Equipment Effectiveness through maintenance management in order to achieve company Key Performance Indicators (KPIs). Otherwise, the mill has to be frustrated with the machine breakdowns and downtimes without a proper preventive maintenance program. The following sections identify some of the gaps that exist and discuss the problematic areas that have the potential for the palm oil mills to become more competitive, sustainable, and generate savings through better performance improvement.

Maintenance is a low priority in Sri Lankan palm oil mills (Accomplish the knowledge and performance gap).

Even though there are several maintenance strategies being practiced in other industries in Sri Lanka, such as Preventive Maintenance (PM), Total Productive Maintenance (TPM), Condition Based Maintenance (CBM) and Reliability Centered Maintenance (RCM), there is no such practice being used in Sri Lankan palm oil mills. Data and information-based maintenance management practices in palm oil mills, not only in Sri Lanka but also in Malaysia, are still low priority, according to the evidence of recent research (Shamsuddin, Masjuki, Hassan, & Zahari, 2004). Lack of understanding or knowledge about the importance of equipment in organizational performance is one of the main obstacles. Therefore, one kind of target is to fill this knowledge gap of Sri Lankan palm oil mills' authorities on OEE and bring the Sri Lankan palm oil sector up to world-standard level.

Because of low priority, there is no adequate, accurate data and information on breakdowns and downtimes on a daily basis in the mill. Without a proper preventive maintenance program, the management has to deal with several unexpected machine failures, some of which last more than a month. Furthermore, as there is no such comparison of performance between standard palm oil mills and Sri Lankan mills, the management does not know their level of performance. On the other hand, as there is no such comparison research of Sri Lankan palm oil mills with standard palm oil mills, the performance of the Sri Lankan palm oil mills is well below the benchmark level. Therefore, this kind of research may be useful to Sri Lankan palm oil mills in order to dramatically improve their performance with the above practices by addressing major losses and wastes associated with the production process systems (Gupta, Gunalay, & Srinivasan, 2001).

1.3 Research questions

1. What is the measurement of Overall Equipment Effectiveness of ABZ Company?
2. Which are the factors affecting Overall Equipment Effectiveness of ABZ Company?
3. What is the level of Overall Equipment Effectiveness of ABZ Company in comparison to Malaysian Palm Oil Mills?
4. How can the Overall Equipment Effectiveness of ABZ Company be improved?

1.4 Research objectives

1. To measure the Overall Equipment Effectiveness of ABZ Company.
2. To identify the factors affecting Overall Equipment Effectiveness of ABZ Company.
3. To benchmark the level of Overall Equipment Effectiveness of ABZ Company in comparison to Malaysian Palm Oil Mills
4. To find out the solutions to improve Overall Equipment Effectiveness of ABZ Company.

1.5 Scope of the study

The finance department of ABZ has complained several times over the years about its maintenance costs. As per the financial report, it has reported its maximum maintenance cost of 1.8 billion per year as of the year 2021. However, there is no proper mechanism in ABZ to check their performance. As a result of that, their maintenance costs are much higher than those of world-class level mills. This study focuses on the efficiency improvement of the ABZ Company based on overall equipment effectiveness. One of the major palm oil mills in Sri Lanka, ABZ, has been selected for this study in order to improve its profitability based on OEE. This study has been focused on the peak period as the oil palm crop is a seasonal crop. Many theories coming under manufacturing management, such as bottleneck finding, OEE theories, manufacturing strategies, etc., have been utilized in order to conduct successful research.

1.6 Significance of the study

The palm oil industry currently contributes less than 2% of Sri Lanka's GDP and employs over 140000 people. It triggers upstream (oil palm plantations and related equipment businesses) and downstream activities (CPO refining, oleo chemicals, and oleo chemical derivatives industries) and brings in revenues for national development and stability with significant foreign exchange earnings. Currently, Sri Lanka imports nearly 75% of its edible oil requirements from other countries. That means Sri Lanka has a very good opportunity to expand its capacity and hand over this golden crop to the small holders. From that perspective, there may be a plethora of palm oil mills being established in Sri Lanka in the near future. As ABZ is one of the key mills established at an early stage, future mills can take ABZ as an example to develop their mills in the future. Therefore, doing this kind of study will not only be useful to ABZ but also vital for the future mills in Sri Lanka and will contribute to increasing Sri Lanka's GDP at a considerable level (Hannan, 2019).

There are three main factors affecting the low OEE, such as availability loss, performance loss, and quality loss. It can be further elaborated into six big losses: equipment failures, setup and adjustments, idling and minor stops, reduced speeds, processed defects, and reduced yield (Venkatesh, 2006). Even though the mill has faced those kinds of losses every day, as there is no mechanism to evaluate them, it is the most complicated task among them. This research will assist them in comprehending each major loss and its impact on the development. Furthermore, from this kind of study, the mill management can evaluate their performance against the benchmark of world-class Malaysian mills.

1.7 Limitations

As the oil palm crop is a seasonal crop, this study has been focused on the peak period from October to March. There are only two shifts running the process, and in the off-peak season, the production will be stopped at 10 pm due to unavailability of the crop. Therefore, this would be useful at peak time instead of off-peak time.

In the current situation, ABZ uses only manual data handling. There is no integrated technology like System, Applications, and Products in Data Processing (SAP) or Enterprise Resource Planning (ERP) system to analyze machine maintenance data automatically. Hence, calculation and relying on the data of Sri Lankan mills is somewhat difficult to compare to other developed countries.

1.8 Proposed outline of the thesis

Chapter Two elaborates on the strategic importance of maintenance and TPM's performance indicator, OEE. It discusses how to measure performance, then identifies gaps between the current and desired outcome of the performance, and thereafter provides solutions to close those gaps in order to succeed in the business. Research scope and objectives are based on improving the existing OEE in order to achieve profitability. Chapter two elaborates on literature that qualifies the history of maintenance management and OEE, its strategies, the performance measurement revolution, and the theoretical background. Chapter three discusses the research framework, model, and methodology and the gap between theory and practice in the OEE system at palm oil mills. In Chapter four, it discusses the results of calculation, data analysis, enumeration, validity and reliability of data, and finally, a comparison of palm oil mills in Malaysia and Sri Lanka. In chapters five and six, it includes conclusions, recommendations, and contributions that identify theory and practice gaps in OEE performance at Sri Lankan palm oil mills.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Overall Equipment Effectiveness

Overall Equipment Effectiveness (OEE) is an essential term that is used to evaluate how efficiently a manufacturer's operation is being used, and the ultimate goal of OEE measurement is continuous improvement of the process. Furthermore, it supports identifying a problem in the manufacturing process and also evaluating which percentage of manufacturing time is actually productive and fixing it while giving a standardized gauge for tracking progress. (Trout, 2021).

The information provided by OEE is a measurement of the relative productivity of equipment, and it is useful to monitor the impact of remedial efforts for further improvements. Generally, the loss of productivity is determined through the analysis of historical equipment performance and production. From two perspectives, the impact of the loss of productivity can be analyzed from two perspectives: either by frequency of loss or by impact of loss. Both of the perspectives are embedded in the term OEE. (Pomorski, 2004).

The equipment effectiveness can be demonstrated in two ways: chronic, which means recurrent gaps between the actual equipment effectiveness and optimal value; or sporadically, which means a variation of a sudden or unusual increase in the efficiency of the external agency or the range of typical and expected. OEE highlights the six major losses as the cause of production equipment not operating normally. Machine availability is determined through downtime losses, which can be further elaborated into breakdown losses, setup and adjustment losses. The next type of loss is speed loss due to minor stoppages and reduced speeds. They are very useful for measuring the performance rate of a particular machine. Rework and yield losses are defined as quality losses to determine the quality rate for the equipment. (Tajiri & Gotoh, 1992).

2.1.1 Importance of OEE for worldwide industries

OEE is a very important tool, both as a benchmark and a baseline. As a benchmark, it can be used to compare the performance of a given production asset to industry standards, to similar in-house assets, or to results for different shifts working on the same asset.

As a baseline, it can be used to track progress over time in eliminating waste from a given production asset.

As a benchmark, a "good" OEE score can be categorized as follows:

1. An OEE score of 100% means perfect production: manufacturing only good parts as fast as possible with no stop time.

2. An OEE score of 85% is considered world-class for discrete manufacturers. It is well suited for many organizations as a long-term goal.

3. An OEE score of 60% is fairly typical for discrete manufacturers, but indicates there is substantial room for improvement.

4. An OEE score of 40% is not at all uncommon for manufacturing companies that are just starting to track and improve their manufacturing performance. This kind of low-scoring firm can be easily improved through straightforward measures by tracking stop time reasons and addressing the largest sources of downtime.

(OEE (Overall Equipment Effectiveness), 2021; Trout, 2021)

In achieving production targets, there are a number of advantages to implementing an overall equipment effectiveness strategy as a powerful tool. It allows all the time to take a proactive approach by tweaking manufacturing processes in real time, reducing downtime, increasing capacity, reducing costs, improving quality and increasing efficiency. (Trout, 2021)

Return of Investment (ROI) for Equipment: Companies invest heavily in machinery, so it is vital to maximize the return on this investment. It can use an OEE strategy to produce 15% more product on the same equipment at the same time, which has a significant impact on profit.

Increase competitiveness: Manufacturers always strive to reduce losses during production to achieve maximum competitiveness. It can take remedial actions immediately using data from an OEE report, which helps to identify bottlenecks in production. Quality and competitiveness go hand in hand, and OEE's quality metric can help to identify problems in production causing scrap or reworked parts.

Cutting machinery Costs: An OEE strategy helps to understand the equipment's actual working performance. It also alerts us to identify issues that may lead to future breakdowns and repairs. Overall equipment effectiveness lets us anticipate potential machine failure, reducing maintenance costs and downtime.

Maximize workforce productivity: Information like operator downtime, revealing productivity data and pinpointing long changeovers or setup times, helps appropriately allot resources, identify where excess capacity is occurring and determine where new hires are needed.

Easily visualize performance: Overall equipment effectiveness emphasizes the visibility of production problems. By highlighting the biggest sources of productivity losses into one single percentage, everyone can recognize what's working and where improvement is needed.

(Trout, 2021)

2.1.2 Factors affecting OEE

Available losses

1. Equipment Failure: Even if the machinery is scheduled for production, it may be halted due to unplanned downtimes such as machine breakdowns, unplanned maintenance stops, and tooling failures.
2. Setup and Adjustments: This is production downtime due to changeovers, machine and tooling adjustments, planned maintenance, inspections, and setup/ warm-up time. (Trout, 2021)

Performance losses

1. Idling and Minor Stops: This is the equipment stops for a short period of time due to jams, flow obstructions, wrong settings or cleaning.
2. Reduced Speed: Sometimes referred to as "slow cycles," reduced speed is when equipment runs at lower speeds than the ideal cycle time (the fastest possible time). This happens because of worn out or poorly maintained equipment due to poor lubrication practices, substandard materials, and bad environmental conditions. (Trout, 2021)

Performance measures

Throughput rate

The average output of a production process (machine, workstation, line, plant) per unit time is defined as the system's throughput, or sometimes throughput rate.

Eg: parts/hour, jobs/hour, batch/hour etc.

Bottleneck rate

The longest process time consumed in the supply chain for certain demand is called the bottleneck or constraint. The workstation having the maximum utilization rate among others has the lowest rate, which is called the bottleneck rate as it hinders the whole process rate. The capacity rate of the process is determined by the slowest station, which has the maximum throughput time or lowest throughput rate. The bottleneck identification process is a very significant task since it determines the process capacity and also provides guidance to improve the capacity. Time can be saved by eliminating the bottleneck in the process. Saving time in a non-bottleneck activity does not help the process since the throughput rate is limited by the bottleneck. (Process Analysis, 2010)

If the next slowest workstation has a much faster rate than the bottleneck workstation, then the bottleneck is having a major impact on the process capacity. If the next slowest workstation has a slightly faster rate than the bottleneck workstation, then increasing the throughput of the bottleneck will have a limited impact on the process capacity. (Process Analysis, 2010)

Capacity

The maximum possible throughput of a product is called the capacity. Releasing work into the system at or above the capacity causes the system to become unstable due to WIP buildup. The capacity of a series of machineries in an organization is determined by the lowest capacity workstation as it is limited by the bottleneck operation.

Throughput time

Throughput time means the average time taken for a particular job from the beginning of the routing to the final inventory point of the routing.

Utilization

Utilization is the fraction of time that the workstation is not idle due to a lack of parts. This includes the fraction of time the workstation is working on parts or has parts waiting and is unable to work on them due to a machine failure, setup, or other detractor.

(Guizzi, Vespoli, & Santini, 2017)

Quality losses

1. Process Defects: This refers to any defective part manufactured during stable production, including scrapped parts and rework-able parts. Incorrect machine settings and operator or equipment errors are common reasons for process defects.
2. Reduced Yield: Reduced yield refers to defective parts made from startup until stable production is achieved. Like process defects, this can mean scrapped parts and parts that can be reworked. Reduced yield most commonly occurs after changeovers, incorrect settings, and during machine warm-ups. (Trout, 2021)

2.1.3 Maintenance management strategies for OEE improvement

Every manufacturing organization is looking for maintenance functions as a potential source of cost savings and competitive advantages over other competitors. It can save extensive amounts of time, money, and other useful resources in dealing with reliability, availability, and maintainability. Furthermore, performance issues can be eliminated through the proper integration of maintenance functions together with engineering functions and other manufacturing functions. (Moubray, 2003). The leading manufacturing organizations in the world have adopted effective and efficient maintenance strategies over the traditional reactive or breakdown maintenance (BDM) approaches in order to get the total benefits out of them. (Sharma, Kumar, & Kumar, 2005).

These maintenance strategies: condition-based maintenance (CBM), reliability-centered maintenance (RCM), and total productive maintenance (TPM) are discussed briefly in the following sections.

Reactive or Breakdown Maintenance (BDM)

In reactive maintenance, or BDM, it repairs machinery only when it breaks down to bring the equipment back from the failure stage to operational stage. And no prior actions are taken to prevent frequent failures, which account for the usually high maintenance related costs. If there is no such smooth production and there is a fluctuation in production, scrap and rework rates get increased due to down time. Thus, ultimately it results in an increase in overall maintenance costs. BDM is applicable in a situation where customer demand exceeds supply and there are huge profit margins, as its main objective is to run the process as much as possible without any delay. Most organizations traditionally used this type of strategy as an action-oriented or fire-fighting approach to solve production problems. (Pintelon & Gelders, 1992; Sheu & Krajewski, 1994).

Preventive Maintenance (PM)

The primary goal of PM is to reduce the frequency and severity of sporadic failures. It is done at a scheduled time, like weekly, monthly, bi-monthly, half-yearly, or annually, regardless of the condition of the equipment/component, by performing repairs, replacement, overhauling, lubrication, cleaning, and inspection (Gits, 1992). Thus, PM reduces the probability of frequent machinery breakdown by a proper planning schedule of intervals (age-based or calendar-based) for carrying out PM tasks (Dekker, 1996). A decision support system is required in order to implement PM successfully and assess the time.

Condition Based Maintenance (CBM)

The purpose of the CBM strategy is to diagnose the sense of machinery and repair it at the appropriate time in order to reduce the probability of sudden sporadic failures. Vibration-based maintenance, or VBM, involves periodic and continuous collection and interpretation of data. Information from this strategy is vital for maintenance engineers' diagnoses and prognosis of issues related to equipment. To diagnose the related issues and failure mechanisms, the physical conditions such as temperature, vibration, noise, corrosion, etc. would be measured. It can be used as a vibration or condition monitoring technique on most rotating and reciprocating machines, but limitations and deficiency in data coverage and quality reduce its effectiveness and accuracy (Tsang, 1995; Yang, Liang, & Danyluk, 1999; Moubray, 2000).

At the current industrial level, the application of CBM has become popular in process industries, such as paper mills, oil-refineries, sugar mills, and thermal power plants. The condition monitoring system supports identifying potential failures, potential causes for failures, and failure mechanisms in order to effectively implement a "zero-failure strategy."

Reliability Centered Maintenance (RCM)

RCM is a systematic approach used to optimize both preventive and predictive maintenance programs to increase equipment efficiency (uptime, performance, and quality) while focusing on minimizing the maintenance cost. The intention of the RCM strategy is to maintain the system's function rather than restore equipment to an ideal condition. Nowadays, it applies in the areas of fossil power plants, oil-refineries, and other process industries. To achieve the main objective of preserving system function, various failure modes that cause functional failure are identified and prioritized accordingly to reflect their importance in system functioning and the consequences of failure. Failure mode analysis (FMEA) and fault tree analysis (FTA) are used in RCM analysis to find the true cause of failure. RCM analysis is vital to determine the maintenance requirements of any asset and ensure it continues to perform the task without any delay or breakdown. (Backlund & Akersten, 2003; Delzell & Pithan, 1996; Fleming, 2006; Toomey, 2006).

Total Productive Maintenance (TPM)

This innovative concept originated in 1951 in Japan. In 1960, TPM was newly implemented by Nippondenso as a supplier to Toyota with the slogan "Productivity Maintenance with Total Employee Participation". Seiichi Nakajima, Vice Chairman of the JIOPM (Japan Institute of Plant Maintenance), became known as the father of TPM. Then it became famous in the automobile industry and rapidly became part of the corporate culture in companies such as Nissan and Mazda. Thereafter, the TPM concept has been introduced by other industries as well, such as consumer appliances, microelectronics, machine tools, plastics, and many others, as a preventive maintenance strategy. Initially, even though the TPM activities were limited to the production department, nowadays, they are actively applied in administrative and support departments in order to enhance the effectiveness of their own activities. (Nakajima, 1989)

TPM consists of three words. "Total" represents that it is vital from top management to the bottom level of people in the hierarchy. It includes all departments such as operations, maintenance, engineering, stores, purchasing, finance, etc. Productive emphasizes trying to do it while production goes on and minimizes production troubles. Maintenance means keeping the equipment in good condition autonomously by doing necessary repairs, cleaning, and greasing or lubricating on time. Through day-to-day activities involving the total workforce, TPM is a highly useful tool to optimize equipment effectiveness, eliminate breakdowns, and promote autonomous maintenance by operators. (Nakajima, 1989)

Nowadays, autonomous maintenance (AM) programs are conducted for three purposes. The first purpose is to bring the production and maintenance people together to accomplish a common goal, which is to stabilize equipment conditions and halt accelerated deterioration. Secondly, most breakdowns can be prevented by prior detection and treatment of abnormal conditions like temperature, vibration, and sound, etc. For that purpose, the operators have to be trained about their equipment functions, common problems with machinery, and problem-solving techniques. Thirdly, it empowers operators as active partners with maintenance and engineering knowledge in improving overall performance. (Shirose, 1995). The main success factors of TPM are top management support, alignment of management initiatives and change, employee training, autonomy for employees, and communication.

There are three ultimate goals of TPM, such as zero defects, zero accidents, and zero breakdowns. Reduction of the occurrence of predetermined machine breakdowns, which lead to loss, can waste lots of money annually. (Willmott, 1994; Noon, Jenkins, & Lucio, 2000).

The entire edifice of TPM is built and stands on eight pillars: Autonomous Maintenance, Focused Improvements (Kaizen), Autonomous Maintenance, Planned Maintenance, Early Equipment Maintenance (EEM), Quality Maintenance, Training, and Education, Safety, Health & Environment, and Office TPM. (Sangameshwran & Jagannathan, 2002).

There are key implementation factors of autonomous maintenance, such as progressive education and training, cooperation between departments, group activities, and prompt equipment problem treatment by the maintenance department. The three crown jewels of TPM are one-point lessons, team meetings, and activity boards. The purpose of a one-point lesson is to transfer learning or share knowledge about correct procedures. (Nakajima, 1989).

2.1.4 Barriers in TPM implementation

Even though many research papers suggest TPM, in the real world it is very hard to implement within the premises due to reluctance by the organization and a failure to realize the benefits it would obtain. The main driving factor for this sort of management function is the commitment of top management. The program is highly effective only if there is a high level of involvement and commitment from top management. According to the view of a TPM specialist, top management drives the concept of TPM. For the success of implementation, top management has a higher responsibility to communicate the benefits of TPM from the top level to the lower level. Hence, without the support of top management, most TPM programs suffer a premature death most of the time. Organizational resistance to change is also another driving factor. In some cases, most organizations are not willing to allocate or commit resources like manpower, materials, time, and money. (Bakerjan, 1994)

In the majority of cases, some staff consider TPM an unnecessary expenditure and reduce their allocated resources. The main thing to consider is that TPM implementation takes some time, and top management should be willing to show their patience during the implementation process. Furthermore, most companies maintain a gap between each level of their organizational hierarchy. According to modern consideration, everyone is involved in the decision-making process. For instance, when purchasing a new machine, both the finance department and the engineering department are involved in the decision-making process. That kind of work culture may also affect the TPM implementation process. Most staff in an organization don’t like to work beyond their work boundary, which was already set. As a result, it is the responsibility of top management to unite all employees behind a common goal of success: TPM implementation. Unlike the normal routine activities, TPM implementation is specialized and over employees' scope of work. It requires a specialized set of specific skills considering how things work today in an organization. (Bakerjan, 1994)

If the TPM succeeds, it is because of the employees’ hard work and investment of their time and knowledge. So they required appreciation from their management for the effort they expended. A suitable reward mechanism will encourage people to go beyond their scope. Moreover, most organizations fail to implement TPM because of a lack of knowledge about TPM. Before the announcement of the implementation of the program, it is important to have a visit to an organization in which TPM was successfully implemented. The success of the implementation can be achieved with effective learning and best practice with a competent work force. In parallel with the knowledge of TPM, extensive training plans need to be scheduled by the organization to enhance the competence capacity. An organization should be capable of identifying the requirements of specific knowledge, skills, and management abilities and designing suitable training to develop each of these individual skills. A company needs to take the initiative for TPM implementation with proper training, education, and communication of the benefits of TPM. (Bakerjan, 1994)

2.2 OEE and maintenance management performance evaluation

Different kinds of key performance measuring tools are applied by industries depending on the strategies adopted by them.

2.2.1 Mean time between failures (MTBF)

The first metric for TPM is MTBF (Mean Time Between Failures), which is the average time between each failure. This is measured by machine, and for this metric, the higher the MTBF values are better. This means that breakdowns are less frequent, and that repair costs are lower. As this can be compared on an annual or quarterly basis, MTBF measurement is a direct cost-saving approach. Production output can be increased via low downtime.

$$MTBF = {}^{Total\ uptime}/_{Number\ of\ failures}$$

(Equation: 01)

There is also a debate about planned downtime. Unplanned downtime and variability in uptime performance can be reduced through robust TPM programs. (Miller, 2021)

2.2.2 Mean time to repair (MTTR)

Mean Time to Repair (MTTR) is the next metric, which defines the average time to repair a machine after a failure. For this metric, the lower values of MTTR are preferred. Repairs are quicker and not much more serious with TPM progression. Tracking repair hours and showing an overall reduction is a direct cost savings. On the other hand, extra charges are avoided through cost savings by creating a critical spare parts list. (Miller, 2021)

$$MTTR = {}^{Total\ downtime}/_{Number\ of\ failures}$$

(Equation: 02)

2.2.3 Percent reactive maintenance

The third metric is "Percent Reactive Maintenance" (% Reactive). Here, low values are favored. Industry professionals recommend focusing 20% of their time on reactive maintenance and spending the balance of 80% on preventive, improvement, or scheduled maintenance. The best way to show direct cost savings for this metric is when repairs that were previously outsourced can be done in-house because of less reactive activity, and because of time spent improving maintenance technicians' skills. (Miller, 2021)

2.3 Lean manufacturing practices in Malaysian palm oil mills

2.3.1 Origin of lean

Lean manufacturing was started in a similar way to the Toyota Production System (TPS), which was developed by Shigeo Shingo and Taiichi Ohno in the late 1940's at the Toyoda Motor Car Company. Toyoda first started as a manufacturer of looms for clothes, then diversified into different market segments such as bicycles, engines, trucks, and cars. Due to the management issues, the whole business went bankrupt. Thereafter, they made several changes in order to improve the business. They changed the company name to "Toyota". They made changes to their old, inefficient tools and techniques to achieve TPS goals. Toyota engineers started the journey with the concepts of Henry Ford, Taylor, and Dr. W. Edwards Deming. (Baluch, Abdullah & Mohtar, 2012).

The American automotive industry was in a state of deep competition due to the invasion of Volkswagen and Toyota. Toyota could manufacture a car cheaper than North American cars and sell it in North America despite the huge import tariffs. The number of innovative Japanese cars was increasing daily at a higher rate. Dr. Womack and his group at MIT did a research project called "The Machine that Changed the World" and analyzed the world's automobile industries in different countries. In today's world, Lean Thinking is being applied in many organizations, including banks, service organizations, and hospitals, etc. (Baluch, Abdullah & Mohtar, 2012).

Despite the fact that the North American and European auto industries had adopted the mass production system, Japanese Toyota had begun with mass production and progressed to TPS. Lean manufacturing is, most importantly, a philosophy that leads to continuous improvement and customer satisfaction. It mainly targets lead time reduction and cost reduction while providing quality products on time to customers. This Lean concept has been followed by manufacturing organizations over the last few years to increase their profit level and productivity. They have reached a great level of production efficiency with the application of TPM in parallel with the Lean concept. Many companies have been able to get the benefits of waste elimination and cost reduction through Lean. (Baluch, Abdullah & Mohtar, 2012).

Lean production requires only a smaller number of resources and takes less time to produce products than mass production. Lean maintenance is a primary requirement in order to succeed as a lean manufacturer. However, the Lean maintenance approach and the Lean production approach are not similar because the production and the business dynamics of asset maintenance are different. Production plans are driven by prior scheduled work as they depend on the sales forecast and sales orders. Oppositely, asset maintenance depends on scheduled routine work. (Baluch, Abdullah & Mohtar, 2012).

2.3.2 Implementation of lean manufacturing

Lean principles are applied with the support of an engineer or consultant to the specific industry according to their experience. In order to move towards a lean approach, different combinations of lean tools are used for the value addition process.

In the application process of lean in various businesses, the product flow is chosen in which customers pay for their final product in the market. The value stream is drawn by specifying all the steps invalidated in the production process. The performance of each station as a flow rate or as a cycle time is calculated according to the number of units produced at a specific time period. The workstation with the lowest rate or the highest cycle time is the bottleneck of the entire process. In this method, inventory accumulation at every point is identified and eliminated.

By reducing the variations in the production, the flow of units is optimized and waste is eliminated. By the calculation of average estimated demands per day, per week, per month, and per year, the production is progressed to cover the demand.

As per the pull production system, the production is only done according to the actual customer demand. As a result, no inventory is generated unless it is required by the downstream. Then the production process is improved through the constant analysis of production data to educate staff. (Womack & Jones, 2003; Tsigkas, 2013).

2.3.3 Lean principles

Value identification, waste elimination, and flow generation are the three main lean concepts. In the lean concept, value is the predominant factor. Each and every process in the manufacturing firm has to be evaluated through "whether the customer is willing to pay for each of those sub processes" based on their desires. Sometimes it is very difficult to distinguish as there are many sub processes that are involved. Those processes that don't add value to the final product are considered waste. (Womack & Jones, 2003).

Wastes, or "muda," are encountered in seven ways. Muda means futility, uselessness, superfluity, or wastefulness in Japanese. Transport, inventory, motion, waiting, over-production, over-processing, and defects are seven wastes. Transportation waste happens due to unnecessary moving of materials, products, workers, or processes. Inventories such as raw materials, work-in-process, or finished goods are vital for the smooth flow of production. However, excess inventory can be wasted in production as reworked or non-quality products may result in increasing the lead time, carrying the risk of obsolescence, and requiring more space to store in a warehouse. Motion is another type of waste in the lean system. Motion is simply defined as the movement of people or machines that does not add value to the product or service. There are several reasons for generating waste by motion in the factory premises, for instance, inconsistent work methods, lack of workplace organization, and poor work layouts. Not to mention that motion has a relationship with the core of worker behavior; unnecessary actions, lifting of heavy machinery, take up time and effort, and render workers counterproductive. The fourth one is waiting. Waiting has happened due to the carelessness of our day today at work. It can be described as any idle time between operations or idle time spent waiting for work. It can be mainly caused by workers coupled to machines, inefficient process design, setup changeovers, equipment breakdowns, or material delivery delays taking place. In a production facility, time is a valuable resource and cannot be spared. Overproduction is producing sooner, faster, or in greater quantities than internal or external customers' demand. It can occur due to unnecessary machine requirements, extra inventory, extra storage, and extra material handling. However, it contributes to wasting more useful time. Space requirements are needed to handle overproduction too. The sixth muda type is over-processing, which consists of unnecessary operations or work that could be combined with other work. This is usually caused by unclear customer specifications, work procedures, and standards. The final type of Muda is a defect that requires reworking to fulfill the customers' expectations. This is mainly happening due to incapable processes, lack of training, inadequate tools, and high inventory levels. (Drew, McCallum & Roggenhoffer, 2004).

2.3.4 Lean tools

The Lean philosophy can be achieved mainly through three Lean tools: quality, production processes, and methods. Quality Lean tools are important in order to improve the quality of products. Kaizen is the concept of finding a solution to further improve or optimize the process. Poka-Yoke is the concept of mistake proofing. The operator prevents or corrects the mistakes and takes immediate action in order to prevent the defects.

Production process tools like Just in Time (JIT) are used in order to make the production process more efficient. Cellular manufacturing is the manufacturing of families of parts in a single line or cell. The operator who works in that line or cell is a specialist and arranges all the required tools and materials in the same place in order to maximize the production efficiency. The Japanese original word, Heijunka, or "production leveling," also known as "production smoothing," is a concept of reducing unevenness in the process in order to improve the overall efficiency and utilize the capacity well. For level production, two methods are available, such as leveling by volume and leveling by type.

Method Lean tools are important to assist in optimizing the overall efficiency of the firm. Work standardization is one method used to accurately define each operation and make a systematic determination of the work element sequence. The objective of this method is to clearly communicate the job description. Setup reduction time is another method of interchanging equipment efficiently within a limited time in order to achieve greater flexibility. Line balancing is a method which is used to balance operators and machine time to match the production rate to takt time. (Abdulmalek, Rajgopal & Needy, 2006; Melton, 2005).

2.4 Sri Lankan palm oil mills vs. Malaysian palm oil mills

In the 2020/21 marking year, global palm oil production was about 75.45 million metric tons, up from approximately 73.23 million metric tons in 2019/2020. In that period, Indonesia and Malaysia were the world's leading palm oil exporters. There are 782 palm oil mills distributed in 15 countries. The vast majority of such mills are based in Malaysia (50%) and Indonesia (44%). (Leading producers of palm oil worldwide from 2020/2021, 2021) However, the palm oil production in Sri Lanka is around 12,000 metric tons per year from two palm oil mills. Even though the capacity of the mill is limited only to 12 mt/hr in Sri Lankan palm oil mills, the capacities of the Malaysian and Indonesian mills range from 20 mt/hr (small mills) to 100 mt/hr (larger mills).

The OEE values in every Malaysian mill are over 65%, with a contribution of more than 85% from each of the three factors (availability, performance, and quality). They have taken many initiations, such as TPM, LEAN, TQM, etc., in order to improve OEE. They have been identified as the critical machineries that are related to availability losses in order to run the process consistently.

Baluch, Abdullah, and Mohtar (2012) analyzed the OEE values of Malaysian mills as 0.62, 0.75, 0.71, 0.68, and 0.70 in Johor, Kedah, Melaka, Pahang, and Sabah, respectively. Based on this research, Kedah mill had the highest OEE among others, in which the availability, performance, and quality rate were 0.90, 0.92, and 0.91, respectively. Hence, it needs to target more than 90% contribution from those critical factors in order to achieve more than 75% of OEE.

Siregar, Purba, and Aisyah (2017) investigated the overall equipment effectiveness (OEE) of palm oil mills in Indonesia. Based on the OEE calculation results from palm oil mill PT. XYZ, it has obtained an average of OEE of 65%. With comparison to the OEE standard for the manufacturing industry, 85 of OEE is ideal. Setup/adjustment becomes one of the biggest losses in this case due to inconsistency of time, raw materials of palm fruit that enter the palm oil mill, causing the capacity of the mill to not be reached. Therefore, it is expected that a consistent supply of raw materials will consistently increase the OEE of the mill, thereby reducing downtime and the need for preventive maintenance.

However, as there is no such analysis done in Sri Lankan mills, the position of Sri Lankan mills can be identified with the comparison of world-standard mills. It can be implemented with the initiatives and their approach in Sri Lankan mills in order to achieve good OEE.

2.5 Underpinning theory and theoretical framework

Tsang (2002) has developed a "theoretical framework" for an input-output model based on Scientific Management Theory. According to Tsang (2002), the outputs of the production system, availability, volume, quality, cost of production, and safety, determine the profit of a firm. These outputs are, in their turn, influenced by the maintenance function described below.

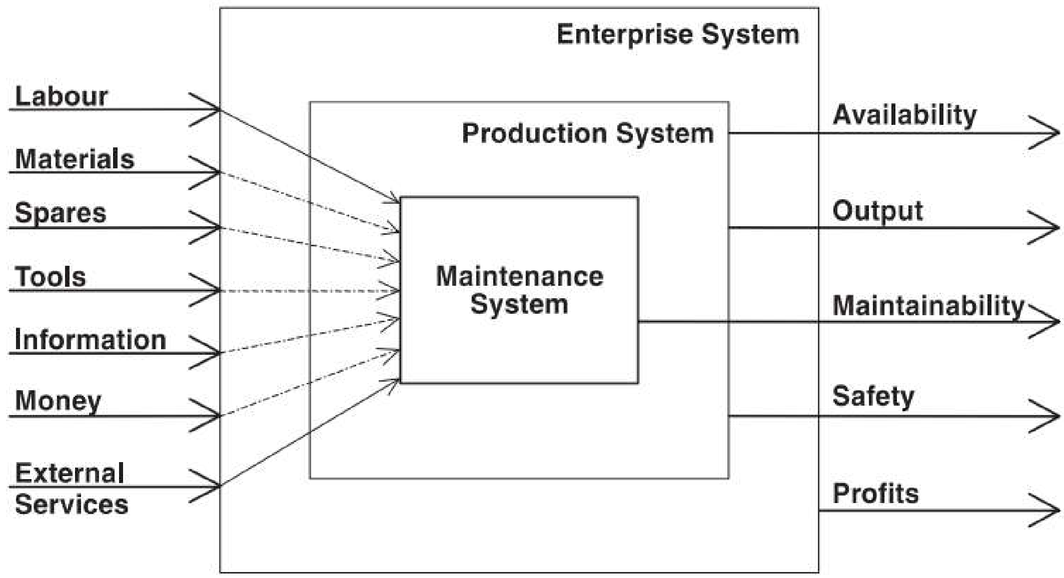

Figure 2.1: Input-output model based on Scientific Management

In this model, the resources that are deployed for maintenance include labor, materials, spares, tools, information, and money. It may influence the availability of production facilities and the volume, quality, and cost of production according to the maintenance performance. Profitability is the major output of this system.

In the developed model, the maintenance management system is influenced by the maintenance management strategies like BDM, PM, TPM, RCM, and CBM.

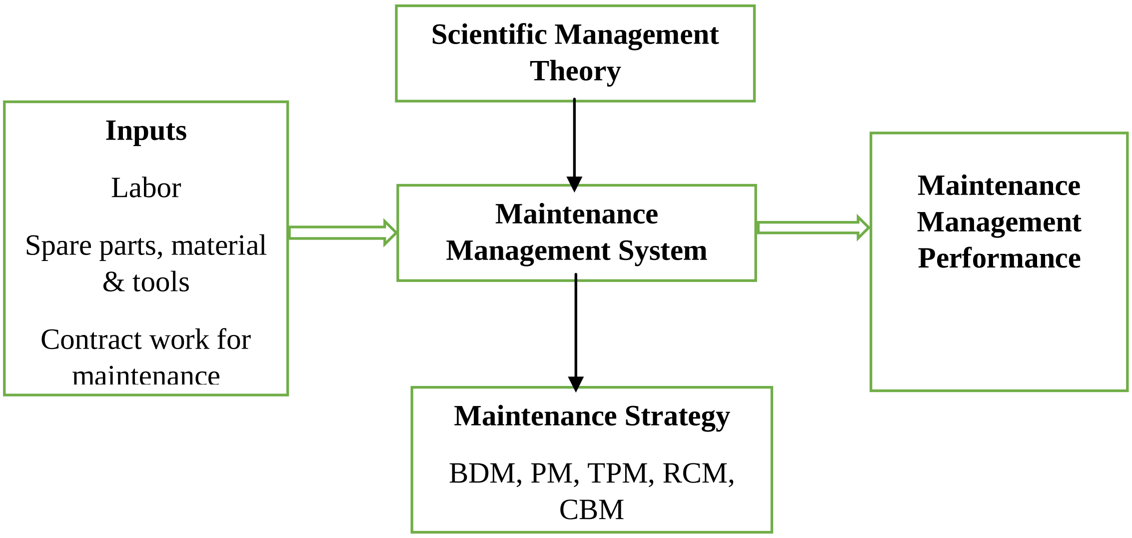

Figure 2.2: Maintenance management system

2.6 Research gap identification

It has elaborated on the practical and theoretical contributions to maintenance performance measurement in palm oil mills. Many authors have suggested several best practices, steps, strategies, models, and activities in order to manage this maintenance function. The aim of scientific management by Taylor was to produce knowledge about how to improve work processes. It was one of the earliest systematical approaches to link management and process improvement as a scientific problem. In the current context, six-sigma and lean manufacturing are considered new trends in scientific management. The developed theoretical framework draws on the "input-output" concept put forward by Tsang (2002).

In this study, the gap between theory and practice will be discussed. All the maintenance inputs such as labor, spare-parts, materials, and tools are the independent variables (IV) of this model. It ensures better performance of the maintenance system by adopting best maintenance strategies like TPM, BDM, PM, RCM, and CBM (moderator variables) which drive the whole system. However, measuring OEE to evaluate maintenance system management is the core element of a well-developed research model, and it has not yet converged to that kind of measurable level.

CHAPTER 3: METHODOLOGY

3.1 Introduction to research design

The research design and methodology for this study includes a guided pathway for the collection, measurement, and analysis of data in order to achieve a final outcome. It is the plan and structure of the investigation that are vital for the reader in order to understand the pathway of the research. This study utilizes several statistical methods like SPSS and Minitab since the purpose of this research is to measure and analyze the overall equipment effectiveness of the ABZ Company.

Maintenance management takes place as an integral part of production and operations, where performance measurement is a critical success factor in business improvement. For more than 30 years, a lot of literature has been focused on developing relevant, integrated, balanced, strategic, and improvement-oriented performance measurement systems. (Slack & Lewis, 2008). A plethora of frameworks have been developed in order to evaluate the performance of a total business organization. Measurement metrics are evolving continually over the decades, and some remain sceptical over a long period of time of any performance measurement system. (Bititci, Turner, & Begemann, 2000)

3.2 Research model

The following figure depicts the research model used here that has been derived from the theoretical framework discussed earlier. It elaborates on how this effective maintenance management system is important for the organization's profit. Independent variables are the inputs for this model, which compromises three main IVs: labor, spare parts, materials and tools, and maintenance contracted out.

In maintenance strategy, "moderator variable" is the core function influenced by this model. Effective maintenance strategies like BDM, PM, TPM, CBM, and RCM may ensure reliable production equipment- reflective of the effective performance of the maintenance management system. The dependent variable is Maintenance Management Performance, where the measurement criteria is OEE.

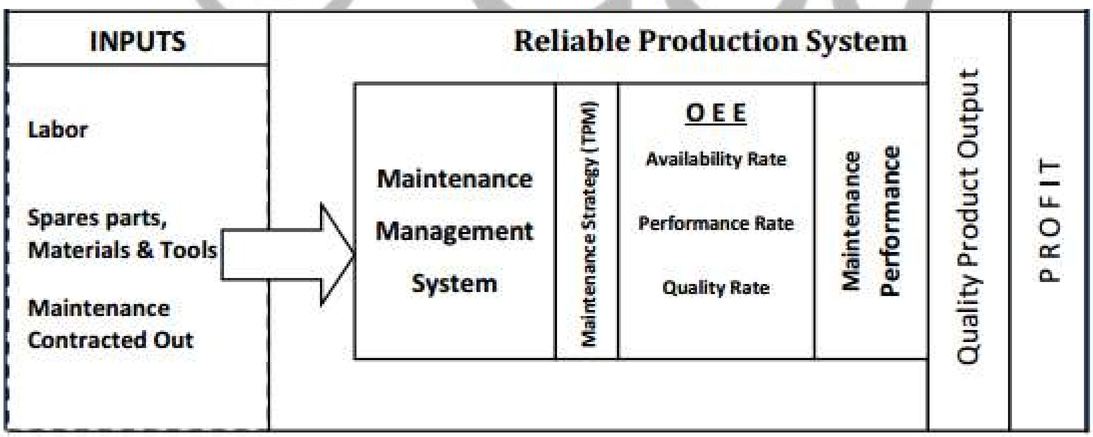

Figure 3.1: Research model system

3.3 Descriptions of variables

3.3.1 Independent Variables (IV)

Independent variables are the inputs for this model, which compromises three main IVs: labor; spare parts, materials, and tools; and maintenance contracted out.

Labor: Labor skills are one important determinant. For having a good OEE value, the skills of the labor force at all levels are very important. Labor skills should be in a wide range, such as engineers, electricians, fitters, welders, machine operators, etc., in order to repair any breakdown immediately, run the process at optimum speed, and do preventive maintenance on time.

Spare parts, materials, and tools: Materials are the consumables used for maintenance purposes like welding rods, chemicals, steel for fabrication, nuts and bolts, etc. Tools include welding machines, grinders, grill machines, and lathe machines, etc. The conditions of the tools, the number of sets of tools available, and the technique of the tools are highly correlated with the final outcome of the system. If the spare parts, materials, and tools are not available at the right time, down time will be increased, and the number of breakdowns will also be increased.

Maintenance contracted out: It should be considered whether the contracted-out jobs or the number of outsourced jobs meet the expectations of the organizations. If the job is not fully completed as per the organization aspect, it affects the final outcome of the system.

3.3.2 Moderating Variables (MV)

In this research, "maintenance strategy" is the moderating variable. It influences the direction and links between independent variables and the dependent variables. Effective maintenance strategies like BDM, PM, TPM, CBM, and RCM are used in different industries. They are the driving factors of all systems.

3.3.3 Dependent Variable (DV)

The dependent variable is the variable being tested and measured in an experiment, and is 'dependent' on the independent variable. If it is given in a mathematical expression as y = f (x), y is the dependent variable of x. In this study, "maintenance management performance" is the dependent variable which is measured through OEE.

3.4 Population, sample design, data collection and research method

The entire group of people or objects to which the researcher wishes to generalize the study findings, or simply the target population of this research, is all the worldwide palm oil mills. A sample or some portion is taken as a representative of a population. This study was carried out at ABZ Palm Oil Processing Pvt. Ltd., Sri Lanka. Data collected is studied while measurements, observations, and interviews are employed on a weekly basis. Descriptive statistics applied in this study provide an initiation for indexes like mean, median, mode, and standard deviation; given these indexes, the researcher then applies statistics to generalize these.

It is not a reliable measure to collect data directly from operators on their performance. There are so many hereditary problems in manual data collection, such as manual forms are often filled in at the end of a shift and may not reflect the truth of what is happening, and the operators' data is not always correct as they are normally struggling with busy operations. This is not an issue with operators' dishonesty. Keeping track of all the time-related activities like set up time, run time, and down time is not a very easy task for them. Proper sensors were set up in order to tackle real-time data of downtime, startup time, stop time, and breakdowns of main machineries such as sterilizers, press machines, boilers, turbines, centrifuges, and kernel expellers. Then a research committee with five trainees from the University of Moratuwa was assigned to complete a given template (Table 3.1) according to each and every machine's details. Members of the research committee gathered primary data in the months of January and February. Then the secondary data was collected from the past log book and the data sheets of the mill for the last two years. Secondary data from other top Malaysian palm oil mills was also gathered.

Table 3.1: The template for the data collection.

Mill name: ABZ Palm Oil Processing Pvt. Ltd.				
		Date		
Descriptions		**Shift A**	**Shift B**	**Total**
FFB Processing capacity				
Total Mill hrs worked				
Break down time	**Sterilizer station**			
	Press station			
	Settling tank station			
	Oil room station			
	Decanter station			
	Kernel station			

	Kernel expeller station			
Start up and minor stops	**Sterilizer station**			
	Press station			
	Settling tank station			
	Oil room station			
	Decanter station			
	Kernel station			
	Kernel expeller station			
Good quality CPO produced				
Bad quality CPO produced				

The above table describes how the required data was acquired by the research committee using the given template. In that template, they collected data from all the machines in every station for both shifts. Each and every breakdown time, start-up and minor stop times, and the reasons for the breakdown were noted down.

There is an annual conference for all palm oil-related industries named the "MPOB International Palm Oil Congress and Exhibition (PIPOC)" in Malaysia for the purpose of discussing the future of the palm oil milling industry. I could get the chance to attend that conference in 2019 and build a good relationship with other palm oil milling managers all over the world. That helped me a lot to collect month-wise data to calculate OEE from January 2020 to December 2020 in palm oil mills situated in Johor, Kedah, Melaka, Pahang, and Sabah. I sent the template for them to collect the data.

Primarily, this quantitative method deals with numerical information being generated and emphasized. This method involves a collection of limited variables known as a "group sample" and a representative sample, which is compared with a few variables in the group of samples. A quantitative study based on overall equipment effectiveness (OEE) was chosen and well explained in detail. Quantitative measurements for the OEE calculation were carried out based on a large number of machines.

Statistical analysis was carried out in order to identify the most critical factors that affect the OEE of ABZ. A factorial base comparison was done with compared to ABZ in order to find the improvement areas. Those areas were much more significant to ABZ's future perspective.

3.4 Conclusion to research design

This study was carried out at ABZ Palm Oil Processing Pvt. Ltd., Sri Lanka. Since the manual data acquisition is not a very reliable source and keeping track of all the time-related activities like set up time, run time, and down time is not a very easy task, proper sensors were set up in order to tackle real-time data of downtime, startup time, stop time, and breakdowns of main machineries such as sterilizers, press machines, boilers, turbines, centrifuges, and kernel expellers. Then a research committee with five trainees from the University of Moratuwa was assigned to complete a given template according to each and every machine's details. Primary data was gathered with the aid of research members for the months of January and February. Then the secondary data was collected from the past log books and the data sheets of the mill for the last two years. Secondary data from other top Malaysian palm oil mills was also gathered in order to compare their performance with that of ABZ.

An OEE calculation was carried out based on breakdowns, setup time, operating time, and other parameters. Afterward, critical factors that affected the OEE of ABZ were identified through the use of statistical data analysis in Minitab 17.0 software. A factorial base comparison was done with ABZ in order to find the improvement areas. Those areas were compared with the world's best mills and are more significant to ABZ's future perspective.

1. • Assign a research committee with 5 trainees from University of Moratuwa
2. • Real time sensors given primary data collection for January and February months according to the given template by the 5 trainees
3. • Collection of secondary data for past year monthly wise data through data sheets
4. • Calculation of Availability rate, performance rate and quality rate
5. • Data analysis of OEE of the year through Descriptive statistics: using Minitab 17.0 (mean, median, mode, min, max etc.)
6. • Identification of the factors impact to the OEE
7. • Comparison of ABZ mill OEE with best Malaysian mills OEE
8. • Find out the solutions to improve the OEE

Figure 3.2: Summary of methodology

CHAPTER 4: RESULTS

4.1 Introduction

This chapter includes the calculation of Overall Equipment Effectiveness (OEE) based on the total mill running time, mill breakdown time, start-up and minor stops, FFB processing capacity, and CPO production. Based on the given equation of availability rate, performance rate, and quality rate, OEE values were calculated for each and every month of the last two years. All the calculated data is included in annex 1 and annex 2. A statistical analysis was conducted with the use of Minitab 17.0 software in Chapter 4.2 with the use of past OEE values from 2017 to 2020. A time series plot of OEE was plotted against each month in order to identify any related pattern. In order to find a correlation between all three factors and their significance to each other, a Pearson correlation analysis has been conducted and tabulated in 4.2.3.

In chapter 4.4, loss time calculation has been done in order to arithmetically measure the impact of loss on the mill from each of those availability, performance, and quality loss rates. Since it is vital to match local mills' performance with world-ranked mills' performance, an OEE value comparison has been done, and the best performer has been compared with the lease performer. Since our ultimate goal is to provide necessary solutions to local mills on how to improve their performance, in Chapter 4.6, bottlenecks in the process have been identified and eliminated.

4.2 Calculation of OEE

According to the data obtained by the research committee, OEE value of 1st of January 2021 was calculated as follows.

FFB processing capacity =14 tons/hr

Total mill hours worked =990 mins

Reported mill breakdown time	=Mill breakdown time for shift A + Mill breakdown time for shift A
Reported mill breakdown time	= 200 mins
Start up and minor stop	= Start up and minor stops for shift A+ Start up and Minor stops for shift B
Total Start up and minor stops	= 90 mins
Total mill downtime	= Mill breakdown time+ Start up and minor stops time
Total mill downtime	= 290 mins
FFB processed	= 228 tons
CPO produced good quality	= 52.44 tons
Oil Extraction Rate (OER)	= 52.44/228
	=23%
CPO production per hour	= 52.44*(228/14)
	= 3.22 tons/hr
Bad quality CPO produced	= 10.2 tons
Availability rate	= 990/ (990+290)
	= 0.77
Performance Rate	$= 52.44 \Big/ \left(\frac{990+290}{60*14*0.23}\right)$
	=0.76
Quality Rate	=52.44/ (52.44+10.2)
	= 0.84
OEE	= 0.77*0.76*0.84
	= 0.49
Availability Loss Time	= 290 mins
Performance Loss Time	= (1-0.76)*(990+290)

= 302.85 mins

Net Operating Time = 990-302.85

=687.14 mins

Value Added Time = 687.14*0.84

=575.25 mins

Quality Loss Time =Net Op. Time- Value Added Time

=687.14-575.25

=111.89 mins

Similarly, OEE calculations were completed for the entire January and February months in 2021. OEE values of January and February months are tabulated in Annex 1 and Annex 2.

4.3 Analysis with Minitab 17.0 software

4.3.1 Time series plot of OEE

OEE values of the past years, from 2017 to 2020, were also calculated to identify any pattern. It is tabulated in Annex 3.

The application of Minitab 17.0 software yielded the following results:

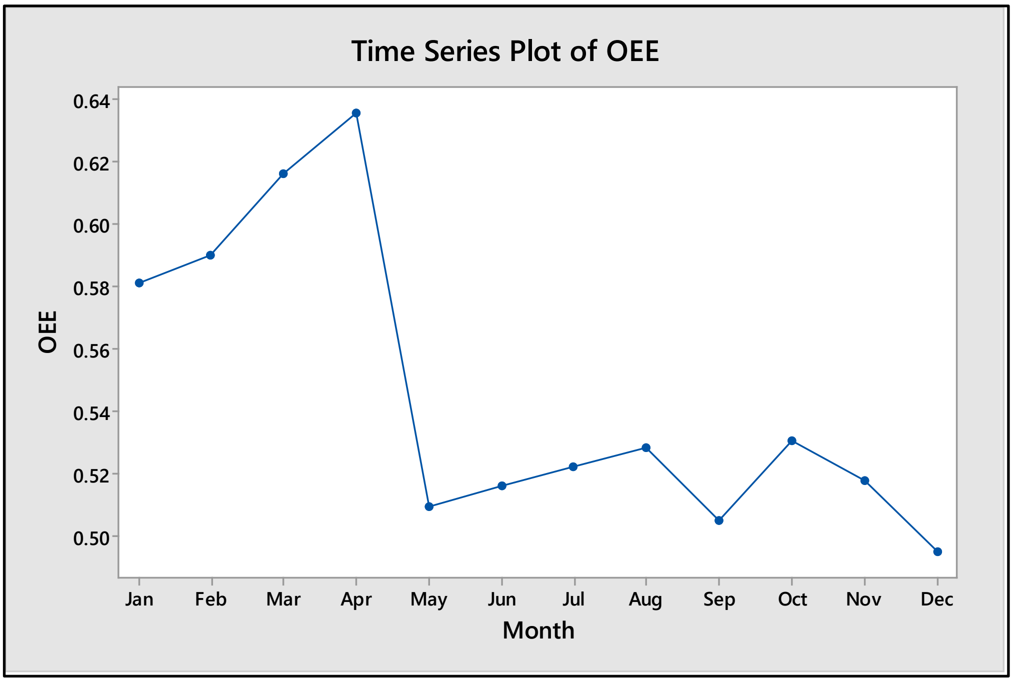

Figure 4.1: Time Series Plot of OEE

According to the above graph, it shows us that OEE values are high in January, February, March, and April. According to the graph, there is a relationship between oil palm seasonality and the OEE. In the off-season period, OEE values are high, while the rest of the time they are low. This might be because of poor capacity in ABZ.

4.3.2 Descriptive statistics: availability rate, performance rate, quality rate, OEE

Table 4.1: Descriptive statistics

Variable Maximum	N	N*	Mean	SE Mean	St. Dev	Minimum	Median
Availability 0.8763	12	0	0.7963	0.0112	0.0389	0.7574	0.7809
Performance Rate 0.75308	12	0	0.73474	0.00368	0.01275	0.71250	0.73991
Quality Rate 0.9879	12	0	0.9311	0.0113	0.0391	0.8700	0.9166
OEE 0.6354	12	0	0.5454	0.0136	0.0472	0.4949	0.5250

The descriptive statistics reveals the statistical evaluation of the parameters in the system. It shows the values of mean, maximum, minimum and standard deviation in the data, with quality having the highest values.

4.3.3 Pearson correlation

The Pearson correlation shows the level of significance of the parameters with reference to each other. From the analysis, it shows that availability and quality are significant in predicting the overall equipment effectiveness, whereas performance is not significant at all.

Table 4.2: Data of Pearson correlation

		Availability Rate(%)	**Performance Rate(%)**	**Quality Rate(%)**	**OEE(%)**
Availability Rate	Pearson Correlation	1	-0.107	0.863	0.979
	Sig(2-tailed)		0.742	0	0
Performance Rate	Pearson Correlation	-0.107	1	-0.377	-0.042
	Sig(2-tailed)	0.742		0.228	0.896
Quality Rate	Pearson Correlation	0.863	-0.377	1	0.907
	Sig(2-tailed)	0	0.228		0
OEE(%)	Pearson Correlation	0.979	-0.042	0.907	1
	Sig(2-tailed)	0	0.896	0	

4.3.4 Multiple regression for OEE

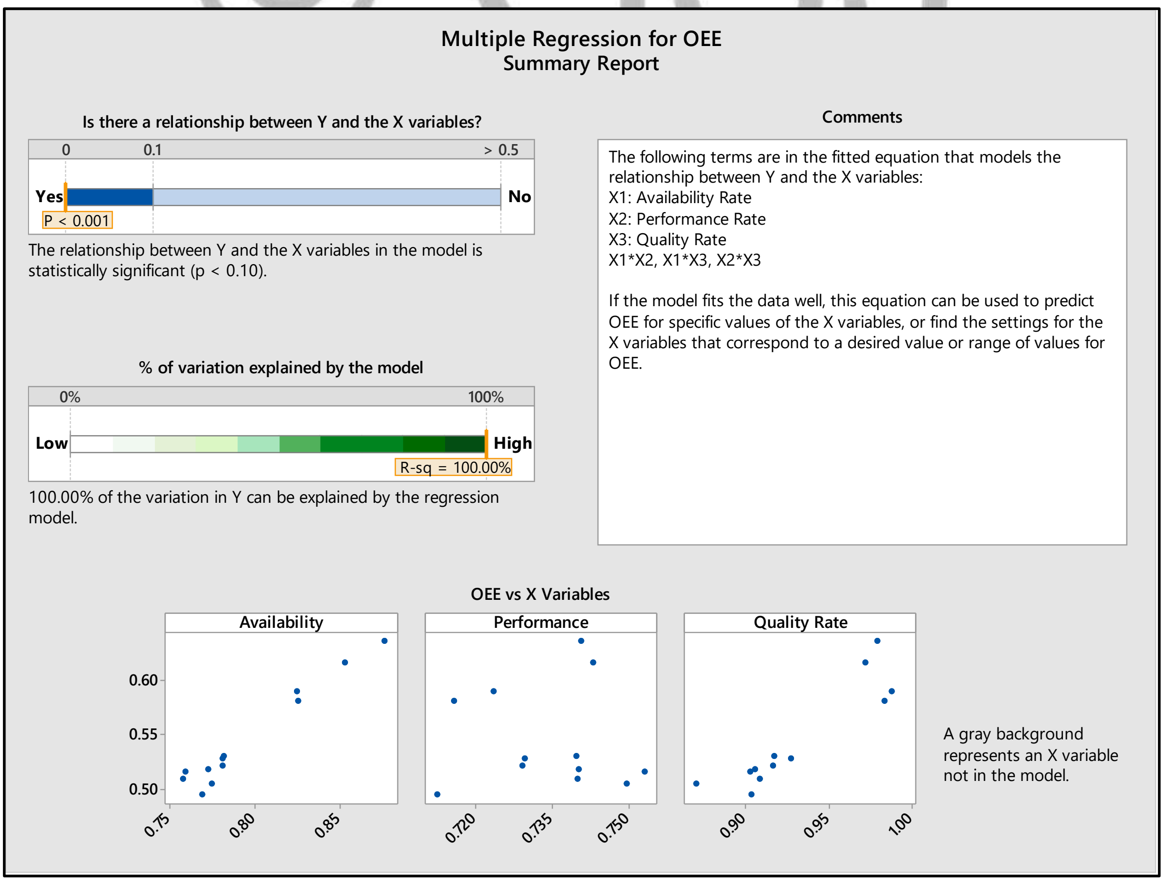

Figure 4.2: Multiple regression for OEE summary report

This Summary Report delivers the "big picture" of the analysis and its results. With a p-value less than 0.001, this report shows that the regression model is statistically significant, with an R-squared value of 100.00%.

4.3.5 Multiple regression for OEE effects

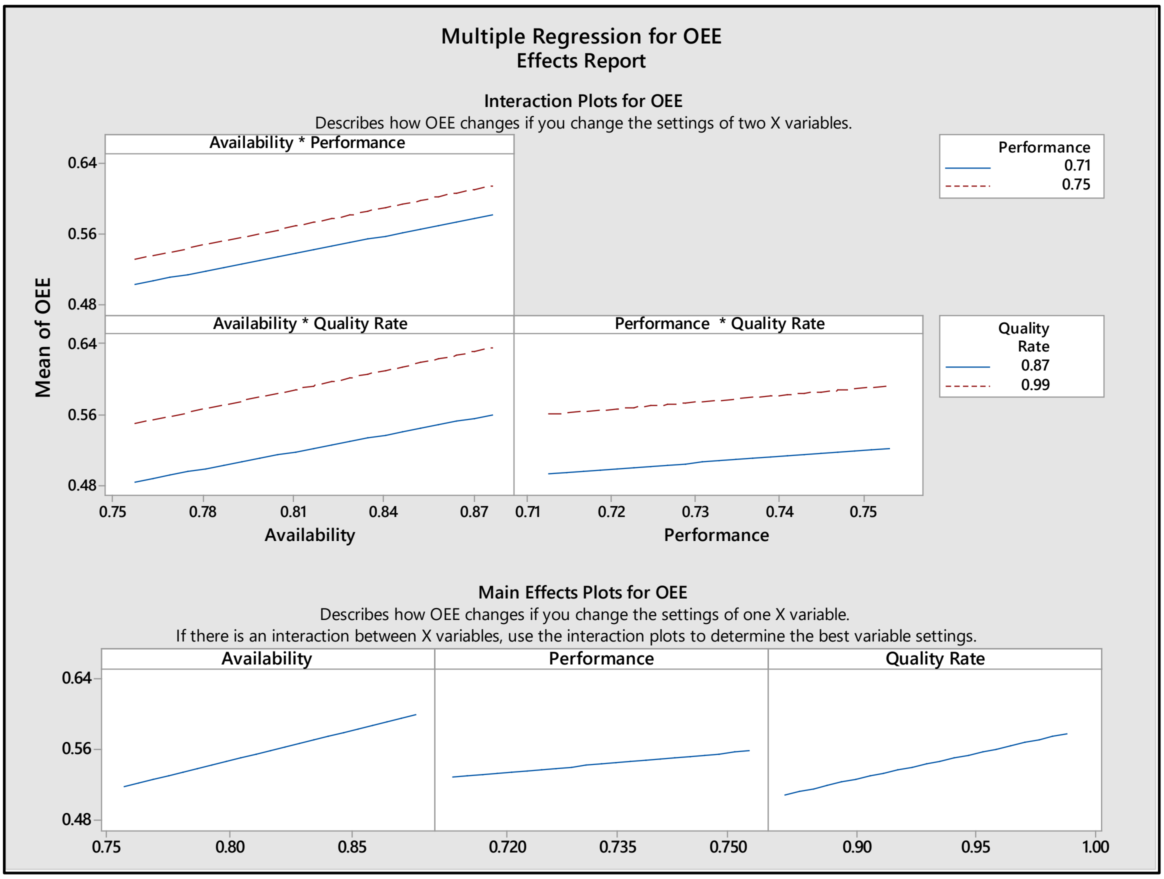

Figure 4.3: Multiple regression for OEE effects report

The Effects Report shows all of the interactions and main effects included in the model. In this report, there is no significant intersection point between the three variables. If one variable is fixed, the other two may vary to impact the final OEE. According to the main effects plots for OEE, availability and quality rate change highly, while performance doesn't show much variation.

4.3.6 Multiple regression for OEE prediction and optimization

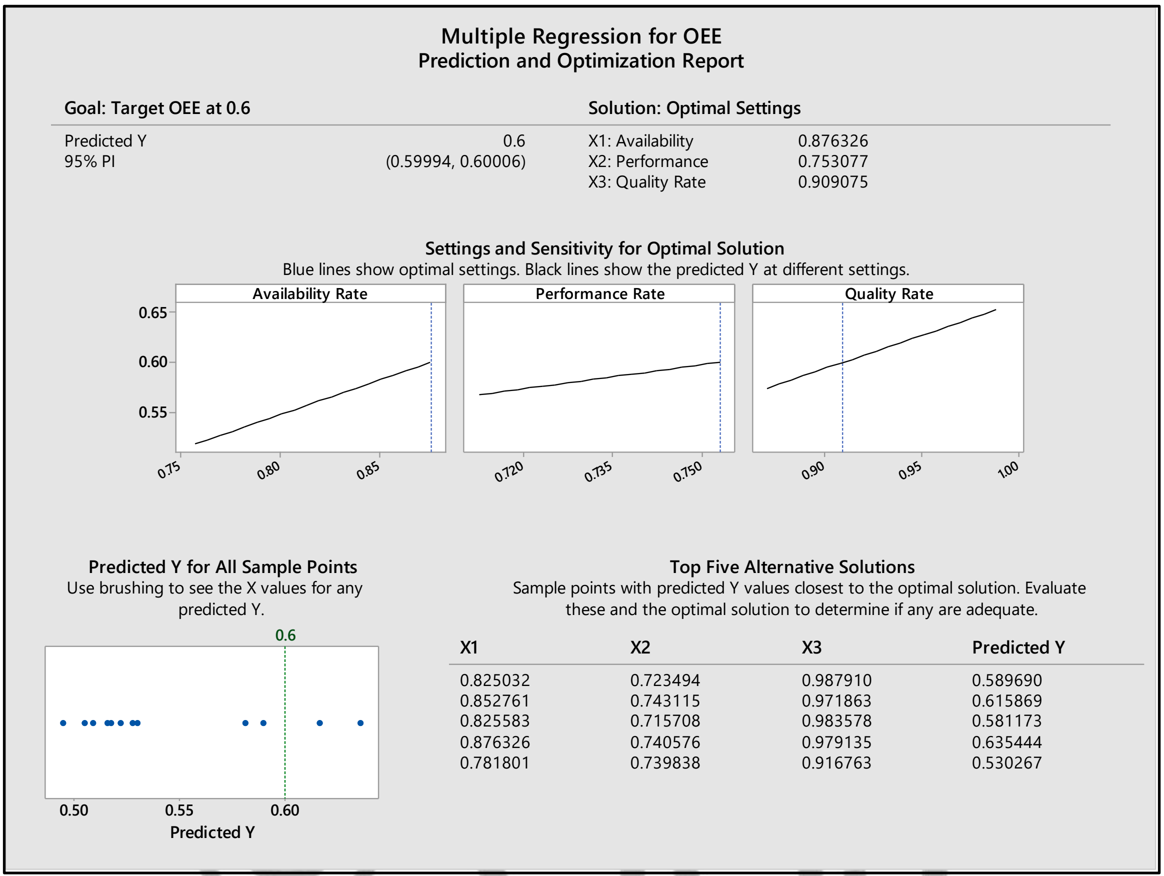

Figure 4.4: Multiple regression for OEE prediction and optimization report

The Prediction and Optimization Report provides solutions for obtaining the targeted OEE of 0.6. The optimal settings for the focal points have been identified as Availability 0.8763, Performance 0.7530, and Quality Rate 0.9090. The model predicts that these settings will deliver an OEE of 0.6, with a prediction interval of 0.5999 to 0.6000.

4.4 Unit root tests for time series

According to econometrics, unit root tests are vital to check whether a time series variable is stationary using an autoregressive model. It is expressed as being stationary only if the mean and variance are constant over a given time period. Moreover, distance (the lag between two time periods) is the main influencing factor for the covariance between the two time periods and not the actual time.

Even though there are a number of test methods such as the Dickey Fuller Test, the Elliott-Rothenberg-Stock Test, Schmidt-Phillips Test, Phillips-Perron Test, the Zivot-Andrews Test, etc., the most basic method of stationarity detection is used by plotting the data and visually checking for trends and seasonal components. (Ozbun, 2021)

By plotting the data and visually checking for trends and seasonal components, the stationarity of a time series model can be determined. According to Annex 6, time series analysis has been plotted considering mean, variance, and seasonality.

4.5 Time loss calculation

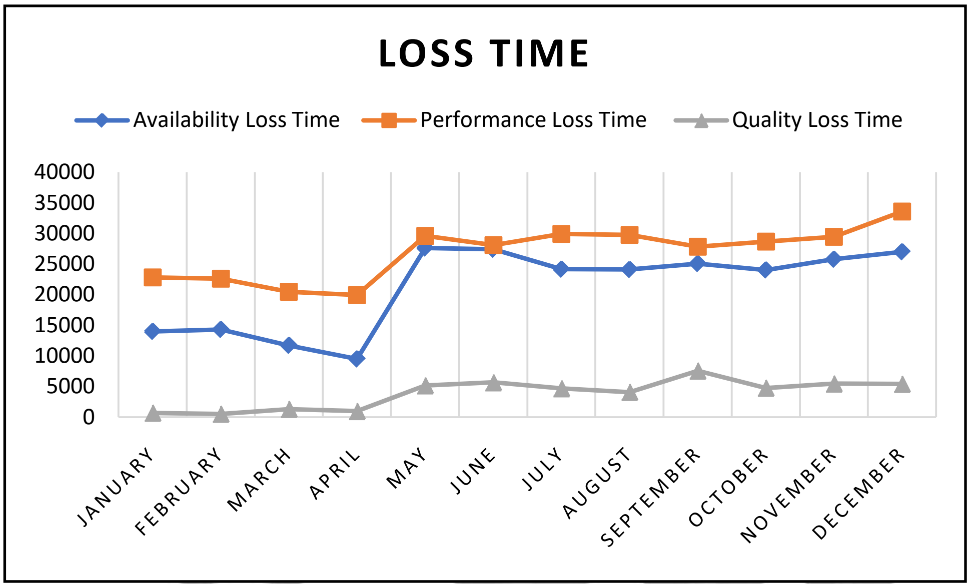

Figure 4.5: Loss time calculation report

The downtime losses, speed losses, and defect losses were calculated and tabulated in Annex 5. Then the loss time graph was obtained as per above. Even though the performance rate variation was low according to the Minitab analysis, the performance loss time was comparatively high in ABZ. This happens due to speed losses in machines. Availability loss time was also comparatively high. This happens due to mill breakdown losses. Because the maintenance department staff has no time to focus on preventive maintenance as the mill runs continuously. Because of insufficient capacity (14 MT/hr), the staff has struggled with breakdowns the last few years.

4.6 Comparison of OEE with other Malaysian mills

From the mill managers in Johor, Kedah, Melaka, Pahang, and Sabah, OEE values were obtained and tabulated in Annex 4.

The following results were obtained by the application of Minitab 17.0 software.

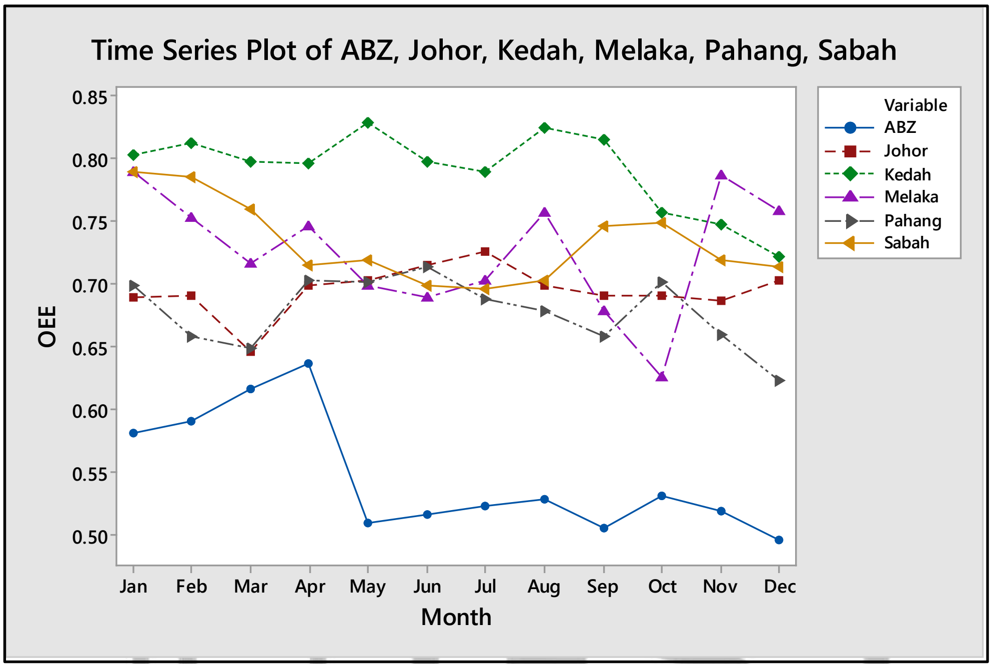

Figure 4.6: Time Series Plot for ABZ and Malaysian Mills

From this plot, it shows that ABZ is in a position that is very below than the other mills OEE.

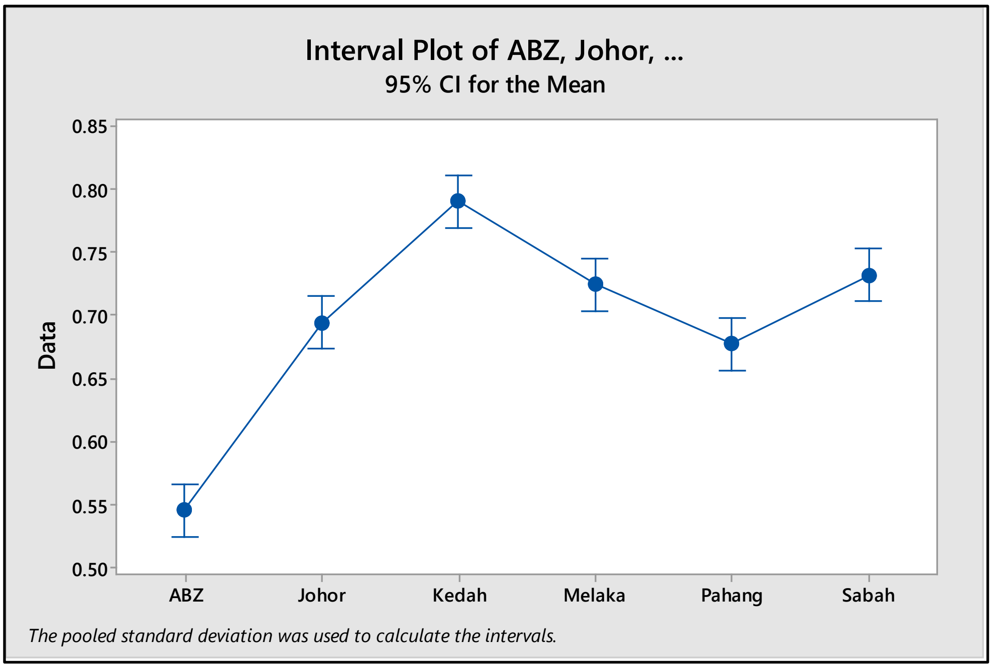

Figure 4.7: Interval Plot of ABZ and other Malaysian Mills

According to the mean and the confidence intervals, it interprets that the ABZ Mean OEE is well below standard levels which need more improvement to achieve that level.

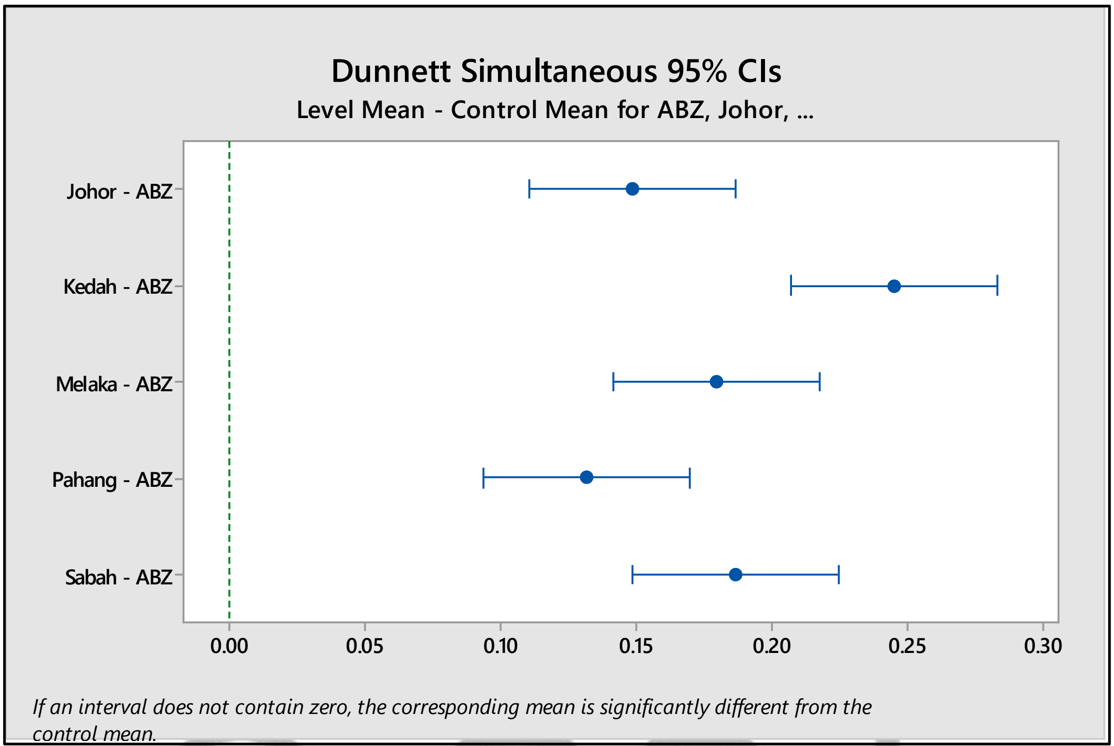

Figure 4.8: Dunnett Simultaneous of ABZ and other Mills

The mean confidence interval difference between Kedah and ABZ is the highest value with the comparison of others. Hence ABZ needs to achieve the level of Kedah in order to improve the OEE.

4.6.1 Factor analysis with other mills

Table 4.3: Data of factor analysis with other mills

Name of the Palm oil Mill	Availability Rate	Performance Rate	Quality Rate	OEE
ABZ	0.7963	0.7347	0.9311	0.5448
Johor	0.8924	0.8457	0.9211	0.6952
Kedah	0.9245	0.9245	0.9247	0.7903

40

Melaka	0.8900	0.9037	0.9012	0.7248
Pahang	0.8752	0.8800	0.8800	0.6778
Sabah	0.8924	0.9200	0.8914	0.7318

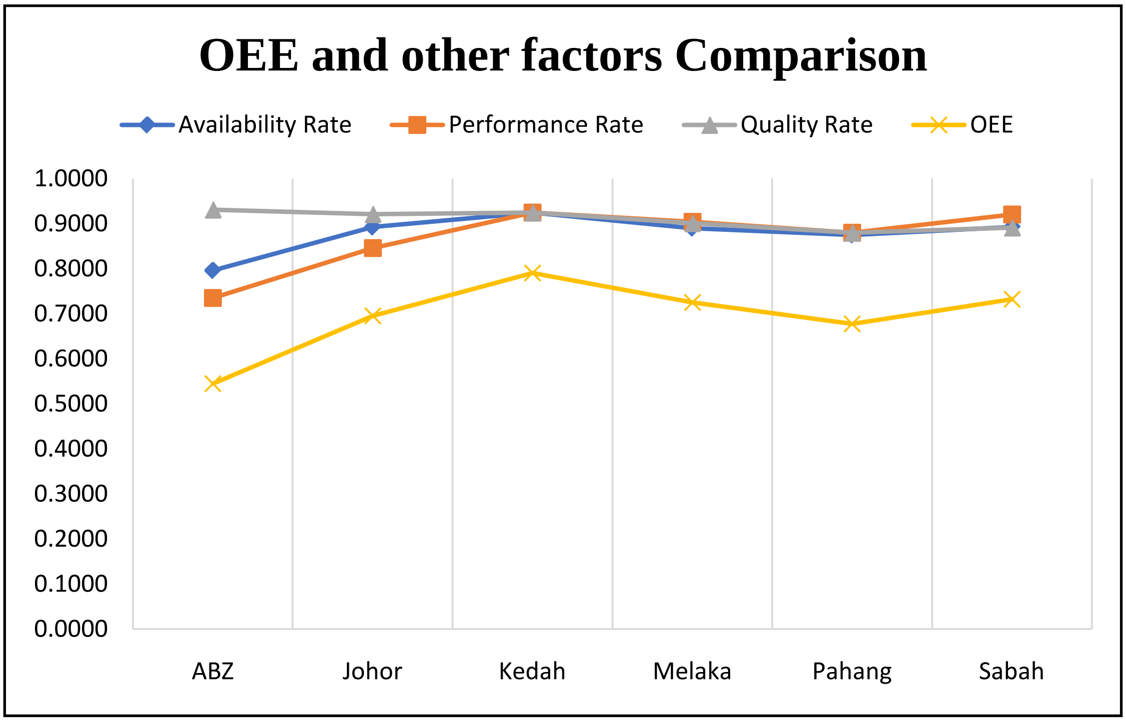

Figure 4.9: OEE and other factors comparison

4.7 Bottlenecks elimination

Several data and work combination charts for the CPO process line, Kernel process line, and kernel meal process line were collected from the LEAN department and production department of the company. In addition to that, MTTF and MTTR data were collected from the Maintenance department. Work combination charts have been shown below for these three selected production lines. These work combination charts were prepared by using the Standard Work Combination Charts.

Table 4.4: Work combination charts for CPO process line

Workstations	Time(min) per batch	Cum Value (min)
Weighing	10	10
Yard	30	40

Sterilization	100	140
Threshing	50	190
Digestion	50	240
Screw pressing	50	290
Oil clarification	25	315
Oil Purification	50	365
CPO storage/Quality checking	20	385

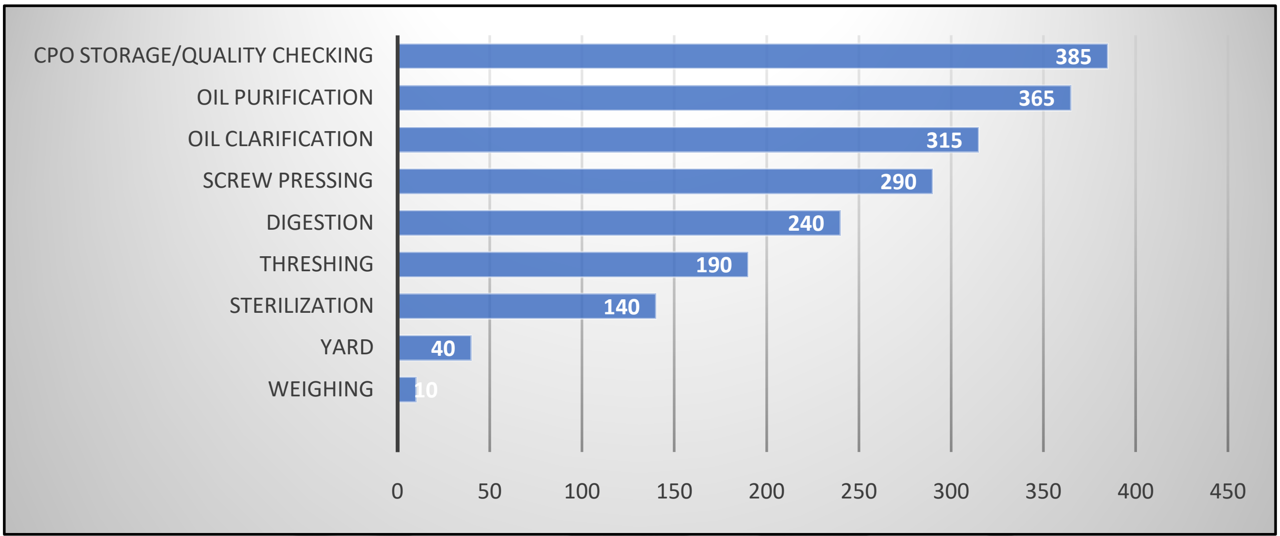

Figure 4.10: Work combination graph for CPO process line

Table 4.5: Work combination charts for Kernel oil process line

Workstation	Time(min) per batch	Cum value(min)
Nut cracking	60	60
Kernel separation	40	100
Kernel heating	100	200
Kernel expelling	60	260
Filter pressing	60	320
Oil storage/Quality checking	20	340

42

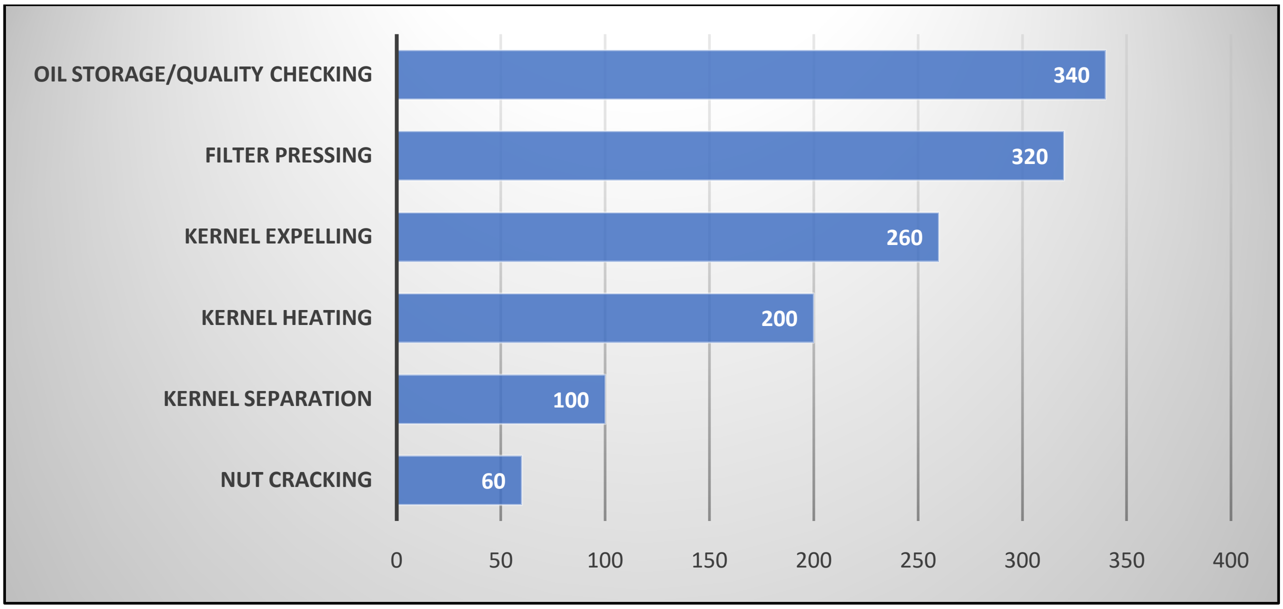

Figure 4.12: Work combination charts for Kernel oil process line

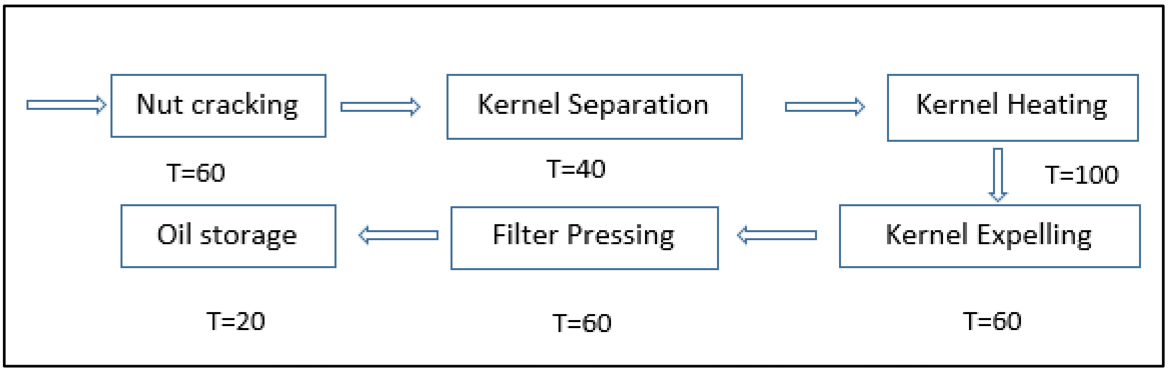

Figure 4.13: Process flow of kernel process line

Table 4.6: Utilization Calculation for Kernel oil process line

Workstation	**Time(min) per batch**	**re(batch/hr)**	**1/re**	**Utilization**
Nut cracking	60	1	1.00	1R
Kernel separation	40	1.5	0.67	0.67R
Kernel heating	100	0.6	1.67	1.67R
Kernel expelling	60	1	1.00	1R
Filter pressing	60	1	1.00	1R
Oil storage/Quality checking	20	3	0.33	0.33R

According to the above calculation, the kernel heating workstation has the highest utilization. The kernel heating workstation is the bottleneck of the process. The production rate of the existing process flow is 0.6 batches per hour.

Table 4.7: Work combination charts for Kernel meal process line

Kernel meal process line	Time(min) per batch	Cum value(min)
Kernel meal 1 weighing	20	20
Kernel meal 1 conditioning	40	60
Kernel meal 1 expelling	30	90
Kernel meal 2 bagging	50	140
Final quality inspection	25	165
Kernel meal 2 weighing	20	185
Meal 2 dispatching	10	195

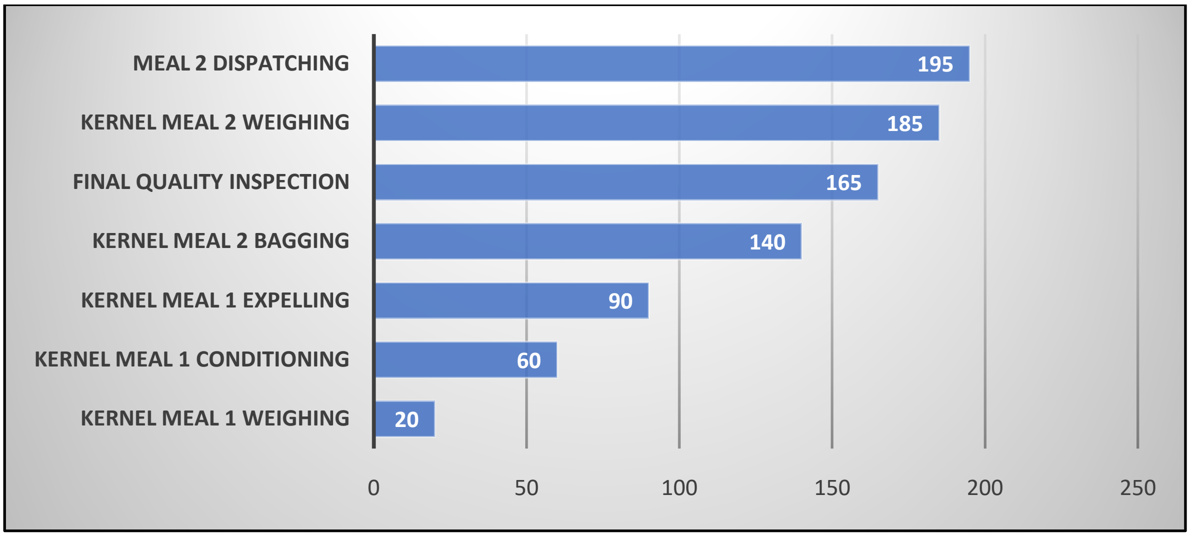

Figure 4.14: Work combination charts for Kernel meal process line

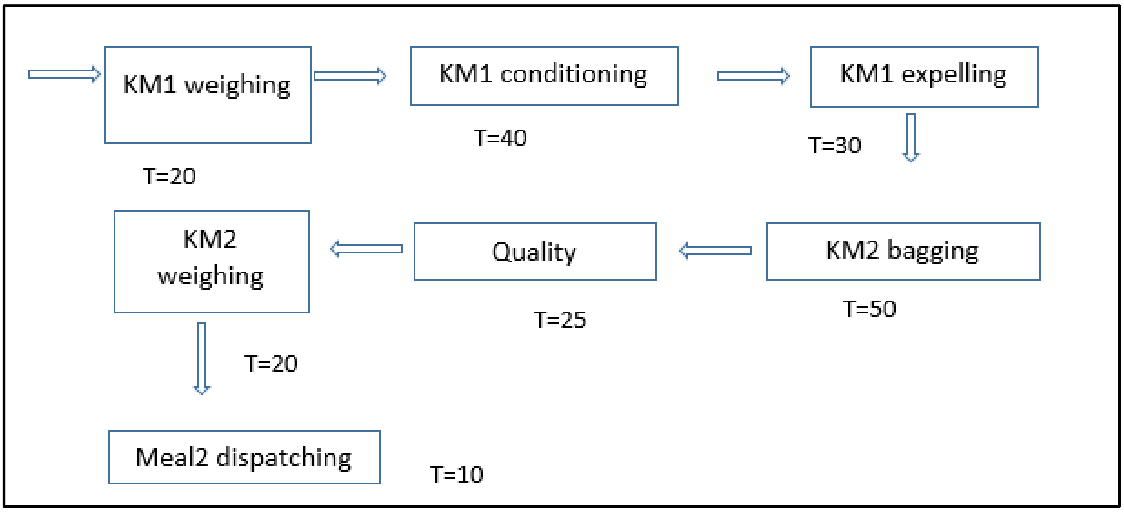

Figure 4.15: Process flow of kernel meal process line

Table 4.8: Utilization calculation for kernel meal process line

Kernel meal process line	Time(min) per batch	re(batch/hr)	1/re	Utilization
Kernel meal 1 weighing	20	3	0.33	0.33R
Kernel meal 1 conditioning	40	1.5	0.67	0.67R
Kernel meal 1 expelling	30	2	0.50	0.50R
Kernel meal 2 bagging	50	1.2	0.83	0.83R
Final quality inspection	25	2.4	0.42	0.42R
Kernel meal 2 weighing	20	3	0.33	0.33R
Meal 2 dispatching	10	6	0.17	0.17R

According to the above calculation, the kernel meal 2 bagging workstation has the highest utilization. The kernel meal 2 bagging workstation is the bottleneck of the process. The production rate of the existing process flow is 1.2 batches per hour.

4.7.1 Bottleneck elimination of CPO process line

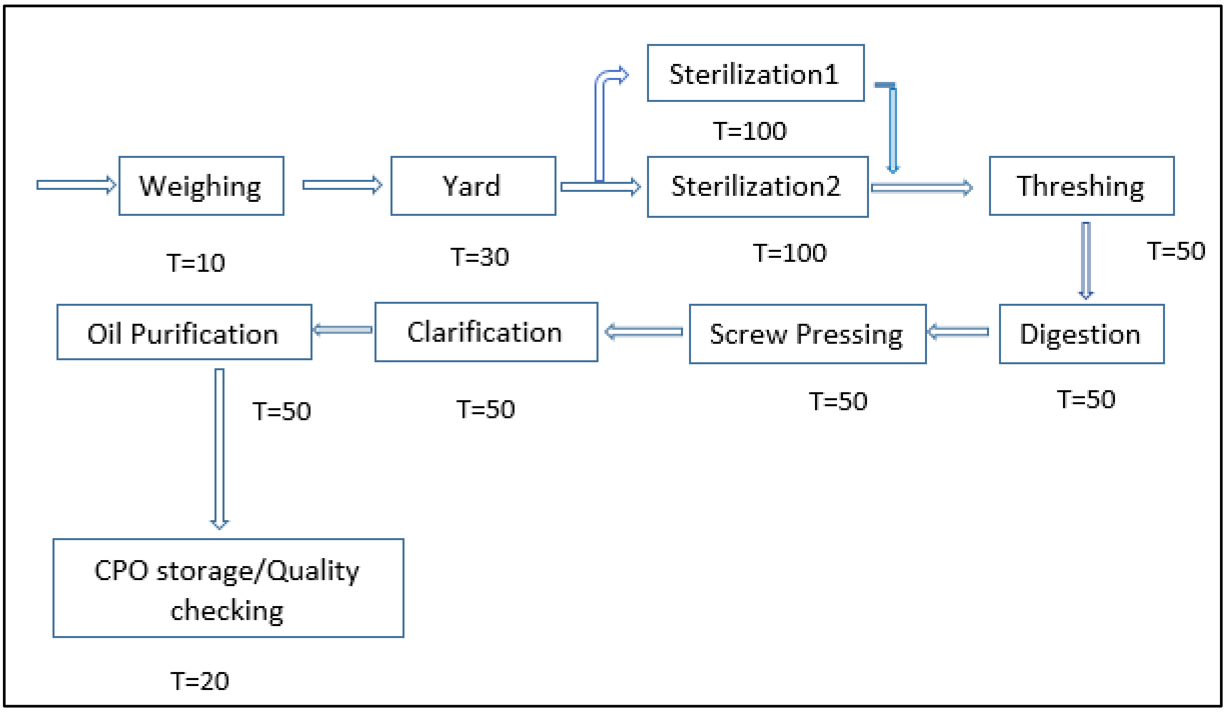

Figure 4.16: Flow chart of bottleneck elimination of CPO process line

Table 4. 9: Calculated data for after bottleneck elimination-CPO process line

Workstation	Time(min) per batch	re(batch/hr)	1/re	Utilization
Weighing	10	6	0.17	0.17R
Yard	30	2	0.50	0.5R
Sterilization	100	1.2	0.83	0.83R
Threshing	50	1.2	0.83	0.83R
Digestion	50	1.2	0.83	0.83R
Screw pressing	50	1.2	0.83	0.83R
Oil clarification	50	1.2	0.83	0.83R
Oil Purification	50	1.2	0.83	0.83R
CPO storage/Quality checking	20	3	0.33	0.33R

The sterilization station is the bottleneck of the CPO process line. Capacity is 0.6 batch/hour. After layout change, it has added another sterilizer in parallel to the sterilizer workstation. The utilization of the sterilizer station will be reduced by 50% and capacity will be increased up to 1.2 batch/hour according to the new process line. Other stations have to wait until the sterilized batch arrival. It needs to maintain the condition (temperature) of settling tanks almost near to 95 C all the time for the optimum settling. If the sterilizer is the bottleneck station, it has to supply steam for other stations long time which is a steam loss for our factory. Hence it can be eliminated by adding another sterilizer to cook another batch and both batches can be handled by existing machineries and tanks.

In the existing process flow, oil clarification has almost half the utilization of other main workstations. That means oil is transferred from the clarification tanks too early without giving it maximum settling time. If the settling time is high, more oil can be recovered. Hence, by increasing the settling time to 50 minutes per batch, it can recover more oil.

4.7.2 Bottleneck elimination of kernel oil process line

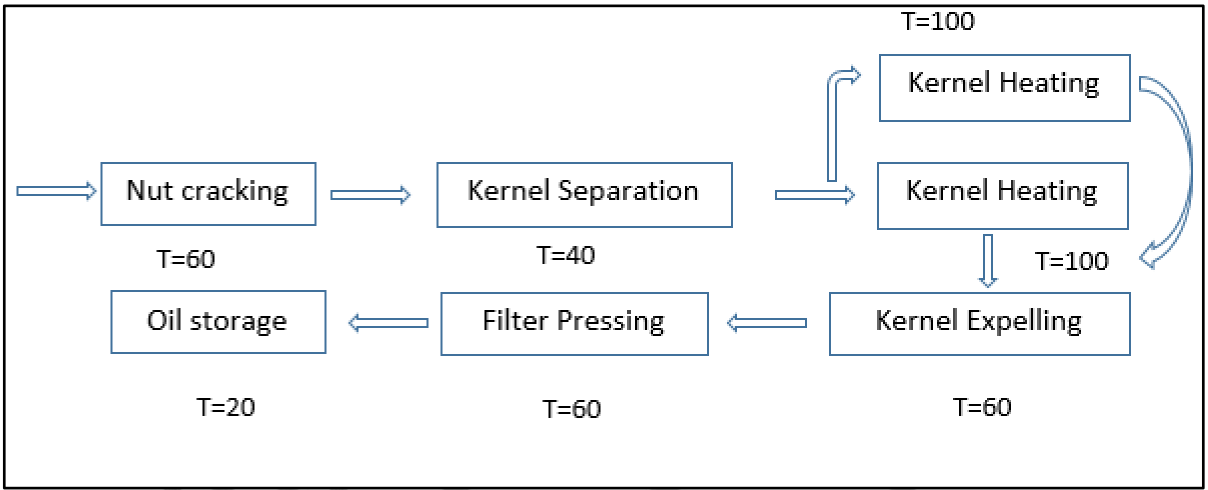

Figure 4.17: Flow chart of bottleneck elimination of Kernel oil process line

Table 4.10: Calculated data for after bottleneck elimination-kernel oil process line

Workstation	Time(min) per batch	re(batch/hr)	1/re	Utilization
Nut cracking	60	1	1.00	1R
Kernel separation	40	1.5	0.67	0.67R
Kernel heating	100	1.2	0.83	0.83R
Kernel expelling	60	1	1.00	1R
Filter pressing	60	1	1.00	1R
Oil storage/Quality checking	20	3	0.33	0.33R

The kernel heating workstation is the bottleneck of the kernel oil process line. Capacity is 0.6 batches per hour. It has added another kernel heating tank in parallel to the existing kernel heating tank. The utilization of the kernel heating workstation will be reduced by 50%, and capacity will be increased by up to 1 batch/hour according to the new process line. Hence, adding another kernel heating tank to condition the kernels would eliminate the bottleneck.

4.7.3 Bottleneck elimination of kernel meal process line

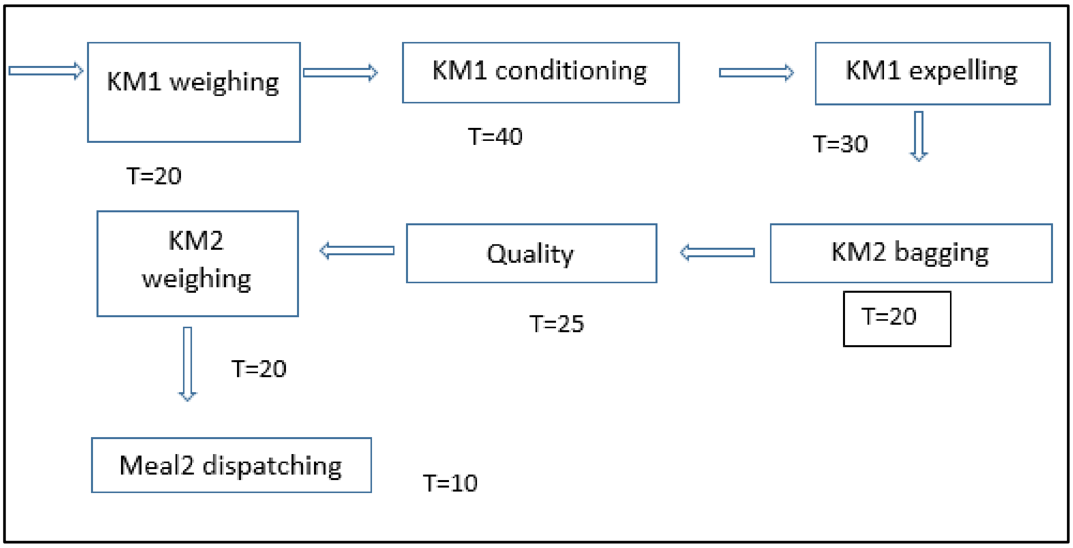

Figure 4. 18: Flow chart of Bottleneck elimination of Kernel meal process line

Table 4. 11: Calculated data for after bottleneck elimination- Kernel Meal process line

Kernel meal process line	Time(min) per batch	re(batch/hr)	1/re	Utilization
Kernel meal 1 weighing	20	3	0.33	0.33R
Kernel meal 1 conditioning	40	1.5	0.67	0.67R
Kernel meal 1 expelling	30	2	0.50	0.50R
Kernel meal 2 bagging	20	3	0.33	0.33R
Final quality inspection	25	2.4	0.42	0.42R
Kernel meal 2 weighing	20	3	0.33	0.33R
Meal 2 dispatching	10	6	0.17	0.17R

As the kernel meal 2 bagging station is the bottleneck, a new advanced technology to reduce the time of the bagging process to 20 minutes/batch can be used. Kernel meal bagging is currently done by hand. Therefore, with the new advanced machinery bagging process, it can eliminate the bottleneck in the kernel meal process line. Utilization of the process is reduced by 60.24% and the production rate of the process is increased by 1.5 batches/hour by adding a new kernel meal bagging machine instead of manual operation

4.8 Capacity increment

As per the previous analysis in section 4.2, 4.3 and 4.4, availability was low because of inadequate capacity in production line.

Oil palm crop receiving for last years are tabulated below.

Table 4. 12: Received FFB data last years

Yr.	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Total
15	1,920	2,409	2,752	3,694	3,728	3,873	3,392	2,995	2,408	2,234	2,186	2,832	**34,424**
16	2,050	3,326	3,680	4,398	4,316	3,734	2,832	2,425	2,419	1,940	1,974	2,094	**35,187**
17	2,532	3,237	3,835	4,866	4,956	4,752	3,857	3,480	3,249	2,897	2,420	2,624	**42,706**
18	2,835	3,208	4,361	4,947	5,176	4,522	4,850	4,161	3,266	3,199	2,941	2,836	**46,302**
19	2,129	4,025	4,278	4,881	5,283	4,535	4,756	4,845	3,889	3,845	3,663	3,497	**49,627**

Considering the FFB forecasted values, it is recommended to double the capacity of the mill. Hence, it can double all the machine requirements in order to fulfill the FFB supply requirement in 2030.

With the identification of bottlenecks, they can be eliminated. Thereafter, it can reduce the setup time of bottleneck machines and increase the efficiency of the machines. Then it leads to an increase in company income. Furthermore, throughput can also be increased by the reduction of setup times of bottleneck machines.

4.9 Conclusion

According to the primary and secondary data acquired from research members and other reliable sources, overall equipment effectiveness (OEE) values were calculated based on the total mill running time, mill breakdown time, start-up and minor stops, FFB processing capacity, and CPO production by the calculation of the availability rate, performance rate, and quality rate.

According to the calculation, the availability ratio was high from January to April, and it depends on the mill breakdown. However, during the peak season, from May to December, the availability ratio was low due to mill breakdown. It is because the maintenance department staff has no time to focus on preventive maintenance as the mill runs continuously in peak season. A statistical analysis was conducted with the use of Minitab 17.0 software in Chapter 4.2 with the use of past OEE values from 2017 to 2020. According to the statistical analysis, there is a relationship between oil palm seasonality and the OEE. In the off-season period, OEE values are high, while the rest of the time they are low.

According to the descriptive statistics under chapter 4.3.2, the data shows the mean, maximum, minimum, and standard deviation values, with quality having the highest values. A time series plot of OEE was plotted against each month in order to identify any related pattern. A Pearson correlation analysis has been conducted and tabulated in 4.2.3. in order to find a correlation between all three factors and their significance to each other. From the analysis, it shows that availability and quality are significant in predicting the overall equipment effectiveness.

According to the Multiple Regression for OEE Effects Report, availability and quality rate change greatly, while performance doesn’t show much variation. According to the loss time graph, the performance loss time was comparatively high in ABZ. This happens due to speed losses in machines. In Chapter 4.6, it is stated that the mean confidence interval difference between Kedah and ABZ is the highest value in the comparison of the others. Hence, ABZ needs to reach the level of Kedah in order to improve the OEE. The bottlenecks that hinder the speed of the process lines were identified in all three CPO, PKO, and kernel meal process lines, and they were eliminated in chapter 4.7.

CHAPTER 5: DISCUSSION

The foremost objectives of this research study are to evaluate the overall equipment effectiveness of the Sri Lankan Palm Oil Mill, to identify the factors affecting OEE, to compare the OEE level with other world-standard mills, and to find solutions to improve OEE. Overall equipment effectiveness is one of the measurements used to evaluate a firm’s performance. In this chapter, it discusses the research findings pertaining to maintenance management performance via a case study of a Sri Lankan palm oil mill.

Sterilizers, centrifuges, decanters, boilers, turbines, expellers, and press machines, among other heavy machinery, have been installed in the ABZ Company, which may experience multiple breakdowns due to an inadequate preventive maintenance plan. From the nominated research committee and the given template, all the relevant data to calculate OEE was collected for the months of January and February. Then the secondary data was collected from the past logbook and the datasheets of the mill for the last two years. Secondary data from other top Malaysian palm oil mills was also gathered.

5.1 OEE measurement

By the calculation of availability rate, performance rate, and quality rate, OEE measurement was also calculated for each and every date in January and February months. Furthermore, OEE values for the past years, from 2017 to 2020, were also calculated to identify any pattern or correlation. The availability ratio was high from January to April, when it depends on the mill breakdown. It means that in off-peak months, mill breakdown time was low. Hence, it had more time to focus on the scheduled preventive maintenance for the mill during off-peak. However, during peak season, from May to December, the availability ratio was low due to mill breakdown. The maintenance department staff had no time to focus on preventive maintenance as the mill ran continuously. The main reason is that the capacity of the mill is still 14 MT/hr. Furthermore, there are idle machines in the process because of bottleneck operations.

5.2 Statistical analysis

Minitab 17.0 was used to analyze the calculated results statistically. According to the time series plot of OEE under section 4.3.1, it is shown that OEE values are high in January, February, March, and April months. According to the graph, there is a relationship between oil palm seasonality and the OEE. In the off-season period, OEE values are high, while the rest of the time they are low.

When it is further analyzed through the descriptive statistics under Section 4.3.2, it reveals the statistical evaluation of the parameters in the system. It shows the values of mean, maximum, minimum and standard deviation in the data, with quality having the highest values. According to the descriptive statistics, the quality rate has a mean value of 0.9311 while the availability rate and performance rate have 0.7963 and 0.73474, respectively.

The Pearson correlation under section 4.3.3 shows the level of significance of the parameters with reference to each other. The following table shows the correlation coefficient value and the direction and strength of the correlation.

Table 5.1: Pearson coefficient analysis

Correlation Coefficient Value	Direction and Strength of Correlation
-1.0	Perfectly negative
-0.8	Strongly negative
-0.5	Moderately negative
-0.2	Weakly negative
0	No association
0.2	Weakly positive
0.5	Moderately positive
0.8	Strongly positive
1.0	Perfectly positive

(Ratnasari, Nazir, Toresano, & Pawiro, 2016)

From the analysis, it shows that availability and quality are significant in predicting the Overall Equipment Effectiveness, unlike performance that is not much significant. The Correlation coefficient values of availability rate, performance rate and quality rate for the effect of OEE with reference to other parameters are 0.979, -0.042, and 0.907 respectively. It implies that availability rate and quality rate have a perfectly positive impact on OEE and performance rate has a very weakly negative impact on OEE. This was further analyzed in Multiple Regression for OEE Effects Report under the section 4.3.5. According to the main effects plots for OEE, availability and quality rate change highly while performance doesn't show much variation.

In section 4.5, loss time has been calculated in order to identify the loss effects on the OEE. By the calculation of downtime losses, speed losses, and defect losses, availability loss time, performance loss time, and quality loss time were obtained. Even though the performance rate variation was low according to the Minitab analysis, the performance loss time is comparatively high in ABZ. This happens due to speed losses in machineries. Availability loss time is also comparatively high. This happens due to mill breakdown losses. Because the maintenance department staff has no time to focus on preventive maintenance as the mill runs continuously. Because of insufficient capacity (14 MT/hr), the staff has struggled with breakdowns over the past years.

5.3 Comparison of OEE and other related factors with Malaysian mills

From the mill managers in Johor, Kedah, Melaka, Pahang, and Sabah, OEE values and other related data were obtained for the purpose of comparison with ABZ Mill. As the Minitab 17.0 software has several tools with regard to comparison, it was used to obtain the Time Series Plot graph, the Interval Plot graph, and the Dunnett Simultaneous graph. According to the time series plot under section 4.6, Kedah mill has the highest OEE range value in comparison to other mills. Generally, it falls in the range of 0.75 to 0.8. According to section 2.1.1, an OEE score of 85% is considered world-class for a discrete manufacturer. It is well suited for many organizations as a long-term goal. Kedah falls into the world-class and industry-accepted category that other organizations need to achieve as a benchmark. Thereafter, OEE values of other mills such as Sabah, Melaka, Johor, and Pahang are in descending order, respectively. Their OEE values fall in between 0.65 and 0.75. That means Sabah, Melaka, Johor, and Pahang mills are at the lower level of world class for discrete manufacturers. However, OEE values of ABZ fall somewhere between 0.5 and 0.6. It means OEE values of ABZ are at a lower level than is fairly typical for discrete manufacturers. However, the positive thing that should be kept in mind is that there is substantial room for improvement in the future.

According to the Dunnett Simultaneous graph (figure 4.8), the confidence interval for the difference between the means for Kedah and ABZ has the highest value at around 0.25. Thereafter, Sabah-ABZ, Melaka-ABZ, Johor-ABZ, and Pahang-ABZ are in descending order. It is not an easy task to get to a world-class level in a short time. It takes some time because each and every person has to commit to it. In the future, ABZ first needs to focus on achieving Pahang mill efficiency as a first step. Thereafter, they should try to achieve the Johor level, Melaka level, Sabah level, and Kedah level. The Kedah level would be the dream level of ABZ, which needs to be tried not more than two years.

According to the factor analysis with other mills in section 4.6.1(table 4.3), Kedah mill has the highest mean OEE among other mills due to the high availability rate of 0.9245, the high performance rate of 0.9245, and the high-quality rate of 0.9247. Second among them is Sabah mill, which has a mean OEE of 0.7318 due to the availability rate of 0.8924, the performance rate of 0.92 and the quality rate of 0.8914. Third among them is Melaka Mill, which has a mean OEE of 0.7248 due to an availability rate of 0.89, a performance rate of 0.9037, and a quality rate of 0.9012. Fourth among them is Johor Mill, which has a mean OEE of 0.6952 due to the availability rate of 0.8924, the performance rate of 0.8457 and the quality rate of 0.9211. Fifth among them is Pahang mill, which has a mean OEE of 0.6778 due to the availability rate of 0.8752, the performance rate of 0.88 and the quality rate of 0.88. ABZ is the final place among them, which has a mean OEE of 0.5448 due to an availability rate of 0.7963, a performance rate of 0.7347, and a quality rate of 0.9311. In comparison to other Malaysian mills, ABZ is the last choice due to its low availability, performance, and quality rates. Hence, in order to improve the efficiency of ABZ, they have to aim to improve all of those factors.

According to the comparison of all three factors: availability rate, performance rate, and quality rate, ABZ has the lowest among all of those availability and performance factors in comparison to each other. The mean availability rate of ABZ in the last few years was 0.7963. However, the mean availability rate of Johor, Kedah, Melaka, Pahang, and Sabah was 0.8924, 0.9245, 0.8900, 0.8752, and 0.8924 respectively. Hence, it should have an improvement in availability rate in order to enhance the OEE in ABZ. The mean performance rate of ABZ last year was 0.7347. However, the mean performance rates of Johor, Kedah, Melaka, Pahang, and Sabah were 0.8457, 0.9245, 0.9037, 0.8800, and 0.9200 respectively. Hence, it should have an improvement in performance rate in order to enhance the OEE in ABZ. The quality rate of ABZ is the highest among the lists due to maintaining good manufacturing practices within the premises.

5.4 OEE improvement through availability improvement

According to this statistical data in the past years, it implies that there is a huge impact on OEE from the availability rate due to high variations. The mean availability rate value is somewhat lower at 0.7963. According to the availability rate equation, it depends on the operating time and the downtime. If the downtime is somewhat low, then it can increase the OEE. In the ABZ mill, the downtime is higher than other Malaysian mills due to insufficient capacity and an improper preventive maintenance schedule. Because of the insufficient capacity, the mill has to run without any stoppage for preventive maintenance. There is no time to do lubrication, spare part repairing, regular cleaning of machines, replacing defective parts, etc.

Preventive maintenance is a systematic approach that aims to predict any kind of future failure of machinery. And it focuses on preventing those catastrophic equipment failures before they occur. For that purpose, the maintenance staff has to do routine inspections of machinery such as vibrations, temperatures, ampere ranges, etc. Normally, the manufacturer provides a lubrication schedule according to its running hours. Hence, using a systematic preventive maintenance schedule after capacity increment would be a better solution to improve the availability ratio and achieve the Malaysian mill standard.

5.5 OEE improvement through performance improvement

According to this statistical data in past years, it implies that there is no huge impact on the OEE from the performance rate because there is less variation in its values. However, that means the performance rate value is somewhat lower at 0.73474. It implies that there is some kind of hidden factor which hinders the OEE value. When it investigates deeper, it discovers two major causes of the decreased performance rate: idling and minor stops, and reduced speed. Speed reduction happens when equipment runs at lower speeds than the ideal cycle time (the fastest possible time). This happens because of worn-out or poorly maintained equipment due to poor lubrication practices, substandard materials, and bad environmental conditions. Machines normally wear out gradually. However, there is no such gradual variation in performance rates from 2017 to 2020. Hence, the performance rate is low because of the idling of machines. There are hidden bottlenecks that have hindered performance over the years.

Considering the above facts, the target was to find hidden bottlenecks that have hindered performance over the years in the ABZ mill. Under section 4.7, it has identified bottlenecks in three parallel process lines: the CPO process line, the kernel process line, and the kernel meal process line in the ABZ mill.

Cycle time data for each and every workstation was collected through the LEAN department and production department of the company, and work combination charts for the CPO process line, kernel process line, and kernel meal process line were tabulated accordingly. According to the utilization calculation for the CPO process line, sterilization has the highest utilization in comparison to other stations, and it is almost double that of others. Hence, the sterilization workstation is the bottleneck of the process. The production rate of the existing process flow is 0.6 batches per hour. After changing the layout, it has added another sterilizer in parallel to the sterilizer workstation. After that, the utilization of the sterilizer station would be reduced by 50% and capacity would be increased by up to 1.2 batches per hour according to the new process line. From the existing CPO line, other stations have to wait until the sterilized batch arrives. It is very difficult since it needs to maintain the condition (temperature) of settling tanks at a very high level (almost 95 °C) all the time for optimum settling. Due to this bottleneck station, it has to supply steam for other stations for a long time, which is an extra steam loss for the factory. Hence, it can be eliminated by adding another sterilizer to cook another batch, and both batches can be handled by existing machineries and tanks in the CPO process line.

The kernel heating workstation is the bottleneck of the kernel oil process line where utilization is 1.67R and production rate is 0.6 batch/hour. Hence, to eliminate the bottleneck, another kernel heating tank has to be added in parallel to the existing kernel heating tank. Thereafter, the utilization of the kernel heating workstation would be reduced by 50% and capacity would be increased by up to 1 batch/hour according to the new process line. Hence, adding another kernel heating tank to condition the kernels would eliminate the bottleneck. Further, it is a very good decision as well to reduce oil loss with kernel meal.

In the kernel meal process line, the kernel meal 2 bagging workstation has the highest utilization. The kernel meal 2 bagging workstation is the bottleneck of the process where the production rate is 1.2 batches/hour and utilization is 0.83R. With the invention of a new advanced technology instead of a manual bagging process to reduce the time of the bagging process, the bottleneck in the kernel meal process line can be eliminated. Utilization of the process would be reduced by 60.24% and the production rate of the process would be increased by 1.5 batches/hour by adding a new kernel meal bagging machine instead of manual operation.

5.6 OEE improvement through capacity improvement

As per section 4.8, in the current situation, ABZ runs continuously without any stoppage. It stops only to repair any serious or critical breakdown events in the mill. In the current scenario, the FFB supply rate to the mill and the FFB processing capacity of the mill are almost the same. As there are only two shifts, the staff has to work continuously. There is no time to do preventive maintenance or any other tool like TPM or Lean, which are described in chapter 2. In section 4.6, it describes the increment the FFB will receive in the upcoming years. The FFB processing capacity of ABZ is 14 MT/hr. That means only a maximum of 300 MT of capacity can be processed due to small repairs. The capacity has to be doubled in order to improve the OEE.

Capacity increment is not a one-step process as the mill staff has to run the process. It needs to purchase heavy machinery and equipment. Hence, in parallel to the current operation, the space availability must be checked first. As the raw material storing capacity has to be increased by the construction of a new yard on the premises as the first step. Then, in the second step, instead of 12 MT horizontal sterilizers, two new 25 MT vertical sterilizers have to be installed. In the third step, another two screw press machines have to be installed, along with another new decanter machine and three centrifuge machines. All other tanks can be fabricated by the ABZ maintenance staff. In the first stage, all the requirements for the CPO production can be fulfilled. In the second stage, a CPKO production line can be installed by purchasing two new kernel expellers. All capacity details are tabulated below.

Table: 5.2: Machine requirement each stations

Equipment	**Capacity**	**Number of machines**
New yard	4000MT	
Sterilizers	25MT/hr	2
Screw press	15 MT/hr	2
Decanter machines	20MT/hr	1
Centrifuges	12MT/hr	3
Vacuum Dryer	3MT/hr	1
Kernel Expellers	1MT/hr	2
Filter press	0.5 MT/hr	1

5.7 Significance of the study and the findings

Although several types of research have been done in the field of OEE in Malaysian and Indonesian mills, there is no research study that has been done in the Sri Lankan context. None of the management personnel at Sri Lankan Mill are aware of the OEE or its contribution to future improvement.

It is imperative that palm oil mills recognize the OEE in order to achieve company KPIs. Without a proper preventive maintenance program or any application of efficiency improvement tools, the mill must be frustrated with machine breakdowns and downtimes. Hence, this study would be applicable in the identification of some of the gaps that exist and improving the problematic areas that have the potential for the palm oil mills to become more competitive, sustainable, and generate savings through better performance.

Even though there are several maintenance strategies being practiced in other industries in Sri Lanka, such as Preventive Maintenance (PM), Total Productive Maintenance (TPM), Condition Based Maintenance (CBM) and Reliability Centered Maintenance (RCM), there is no such practice being practiced in Sri Lankan palm oil mills. This is mainly because of low priority in Sri Lankan palm oil mills and a lack of any long-term profit generation psychology by the management.

According to the research over the years, data and information-based maintenance management practices in palm oil mills are not considered a high priority. As the palm oil business is a high revenue-generating method, they only focus on extending the oil palm hectares in order to increase the profit. However, they rarely consider using cost-reduction tools in order to improve efficiency. Lack of understanding or knowledge about the importance of equipment in organizational performance is one of the main obstacles. Therefore, one kind of target is to fill this knowledge gap of Sri Lankan palm oil mills' authorities on OEE and bring the Sri Lankan palm oil sector to a world-standard level.

Finally, the palm oil sector is one of the revenue generation concepts among other types of vegetable oils for a country. However, the government and society have not understood the importance of it to the country. At the moment, Sri Lanka depends on importing items from other countries. Hence, this study would be important for the Sri Lankan government and society to know the actual significance of this palm oil sector. Furthermore, this may be a new chapter for society to think about the palm oil sector from a different angle in order to develop our country.

In world-class mills, palm oil mills in Malaysia have cooperative systems in order to check the machine-wise performance online. Daily OEE is calculated and it is one of the KPIs for their top managers. Therefore, they have delegated the factors to their bottom-level people in a respective manner. Final OEE is their target, which the Board of Directors always asks for. However, the Sri Lankan palm oil industry has not improved to that level. If there is a sudden breakdown, the maintenance staff will not come to repair it quickly. They are always suffering from insufficient tools. Hence, this study would be important to address all kinds of issues within the factory premises. Then all the relevant issues would be eliminated one by one with this kind of study. All staff would actively participate in reducing all relevant issues if there is a cooperative system to monitor close machine-wise performance daily.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Key findings

Research objective 1: To measure the Overall Equipment Effectiveness of ABZ company.

In section 4.2, the required raw data like daily total mill hours worked, daily mill breakdown time, startup and minor stop time, daily good quality CPO production, and daily bad quality CPO production were obtained for the January and February months. Thereafter, the availability rate, performance rate, and quality rate, OEE measurement were also calculated for each and every date in January and February. As the two months of data are not sufficient to find any correlation and pattern, the past three years of data were obtained according to the factory logbook and data sheets. Thereafter, OEE values for the past years, from 2017 to 2020, were also calculated.

Research objective 2: To identify the factors affecting Overall Equipment Effectiveness of ABZ company.

Considering most of the factors are hidden and very difficult to find, statistical analysis was done by the application of Minitab software. In section 4.3, ABZ has the lowest score of all of those availability and performance factors in comparison to each other. The mean availability rate, performance rate, and quality rate of ABZ in the last three years were 0.7963, 0.7347, and 0.9311, respectively. Hence, ABZ should mainly focus on availability and performance rate in order to improve the OEE.

Research objective 3: To benchmark the level of Overall Equipment Effectiveness of ABZ company with comparison to Malaysian palm oil mills

Kedah mill has the highest OEE range value in comparison to other mills, which fall in the range of 0.75 to 0.8. According to section 2.1.1, an OEE score of 85% is considered world-class for discrete manufacturers. Hence, ABZ should try to achieve that world-class level step-by-step. The OEE level of the Kedah mill would be the benchmark level. So, they can set that as a KPI. However, it is a somewhat difficult task to achieve at once. Therefore, each and every year they need to target that.

Research objective 4: To find out the solutions to improve Overall Equipment Effectiveness of ABZ company.

The availability rate has to be improved in ABZ by the reduction of downtime of the mill. However, there is not sufficient time due to low capacity in order to implement any tools like TPM or Lean. Hence, ABZ should target increasing capacity first. Thereafter, ABZ can reduce downtime through a proper maintenance plan.

When it investigates deeper, it discovers two major causes of the decreased performance rate: idling and minor stops, and reduced speed. Speed reduction happens when equipment runs at lower speeds than the ideal cycle time (the fastest possible time). Hence, through the elimination of bottlenecks in the production line, ABZ would improve the performance rate. In section 4.7, it has identified the sterilizer as the bottleneck, which can be eliminated by the addition of another parallel sterilizer. In the kernel oil processing line, kernel heating is the bottleneck which can be eliminated by the addition of another parallel kernel heating tank. In the kernel meal process, by using a new advanced kernel meal bagging technique, the bottleneck can be eliminated.

6.2 Future studies

Even though this is very significant in the Sri Lankan context, the time duration is not sufficient in order to measure the OEE after the implementation process. The first capacity increment in ABZ should be achieved step by step, not more than a one-year period. Hence, this research needs to continue further with the capacity increment and performance increment solutions. Thereafter, this can be further extended to find the best viable tools or strategies in order to improve the OEE in the Sri Lankan context, because the Malaysian or Indonesian strategies may not be well suited in the Sri Lankan context. Sometimes it may be necessary to use some kind of blend of strategies in order to succeed in business. Hence, further studies may need to be analyzed in future research studies in the ABZ mill.

Furthermore, it can't rely on human data all the time for that kind of critical research. ABZ can be used with a well-developed Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA) system that helps to reduce the errors caused by humans. PLC and SCADA systems are interfaced through communication cables. The SCADAsystem is used to monitor the boiler temperature, pressure, and water level using different sensors, and the corresponding output is given to the PLC, which controls the boiler temperature, pressure, and water level. With the sensors in the system, it automatically senses the system. All the real-time boiler pressure, header pressure, and header temperature data are integrated and shared through the cloud-based ERP system for all the related parties inside and outside the environment. Without human intervention for work studies or motion studies, all real-time data can be obtained. That may be more accurate and precise than human data. (Palm Oil Mill SCADA, 2017)

The Minder Controls SCADA system in sterilizer and boiler operations allows users to monitor system process operations, acknowledge alarms, generate analysis charts and reports, and connect to an external viewer via network connectivity. They provide extensive and comprehensive customization for full integration of SCADA system applications and SCADA software.

Besides, Minder controls also provide advanced monitoring functions for SCADA systems, which are webserver, html-based viewer, and android monitoring apps. This advanced feature enables the user to quickly and easily access critical production data. A detailed report and detailed trending graphs are obtained from the Webserver and HTML-based viewer. Those graphs are very important for analyzing data and changing the parameters accordingly. (Energy Monitoring with Predictive Maintenance at a Palm Oil Mill Plant in Thailand, 2020)

Moreover, this research study is based on efficiency improvement in the factory premises. However, due to the time constraint, this research has not covered the benefits in money or cash. Hence, in the future, this needs to extend up to the profit margin. Then it may show how much money can be saved by the factory from this concept or how much profit can be recovered from this study.

Every palm oil mill in the world runs continuously. They are more focused on the oil extraction rate than efficiency. Hence, this study has to be linked with Oil Extraction Rate. Because that is a well-known KPI for their top managers. Hence, this study should be further analyzed in future under the title "Oil Extraction Rate Improvement through OEE in the Palm Oil Sector."

REFERENCES

Abdulmalek, F. A., Rajgopal, J. & Needy, K. L. (2006). A Classification Scheme for the Process Industry to Guide the Implementation of Lean. *Engineering Management Journal*, 18(2), pp.15-25.

Backlund, F. & Akersten, P. A. (2003). RCM introduction: Process and requirements management aspects. *Journal of Quality in Maintenance Engineering*, 9(3), pp.250- 264.

Bakerjian, R. (1994). Tool and Manufacturing Engineers Handbook. In *Continuous Improvement(4th edition)* (Vol. 7). ASME.

Baluch, N.H., Abdullah, C.S. & Mohtar, S. (2010). Maintenance management performance– An overview towards evaluating Malaysian palm oil mill. *The Asian Journal of Technology Management*

Baluch, N.H., Abdullah, C.S. & Mohtar, S. (2012). Measuring OEE in Malaysian palm oil mills. *Interdisciplinary Journal of Contemporary Research in Business*.

Baluch, N.H., Abdullah, C.S. & Mohtar, S. (2012). TPM and lean maintenance-A critical review. *Interdisciplinary Journal of Contemporary Research in Business (IJCRB).*

Bititci, U. S., Turner, T., & Begemann, C. (2000). Dynamics of performance measurement systems. In *International Journal of Operations & Production Management.* MCB UP Ltd.

Dekker, R. (1996). Applications of maintenance optimization models: A review and analysis. *Reliability Engineering and System Safety*, 51(3), pp.229-240.

Delzell, J. & Pithan, J. (1996). RCM process yields surprising results. *Power Engineering, 100*(11).

Drew, J., McCullum, B. & Roggenhofer, S. (2004). *Journey to Lean: Making Operational Change Stick*. Virginia: Palgrave MacMillan.

Energy Monitoring with Predictive Maintenance at a Palm Oil Mill Plant in Thailand. (2020, November 4). Retrieved January 10, 2021, from ICP DAS Blog: https://icpdas.blog/2020/11/04/energy-monitoring-with-predictive-maintenance-at-a-palm-oil-mill-plant-in-thailand/

Fleming, S. A. (2006). FAA’s proposed plan for implementing a reliability centered maintenance process for air traffic control equipment: GAO-07-81R. *GAO Reports*, pp.1-16.

Gits, C. (1992). Design of maintenance concepts. *International Journal of Production Economics, 24*(3), pp. 217-226

Gupta, D., Günalay, Y. & Srinivasan, M.M. (2001). The relationship between preventive maintenance and manufacturing system performance. *European Journal of Operational Research, 132*(1).

Hannan, S. (2019). *Palm oil industry hit*. Retrieved January 25, 2021, from The morning: http://www.themorning.lk/palm-oil-industry-hit/

History and Origin. (2014, January 1). Retrieved from The Oil Palm: http://theoilpalm.org/history-and-origin/

Ismail, A. R., Ismail, R., Zulkifli, R., Makhtar, N. K., & Deros, B. M. (2009). A study on implementation of preventive maintenance programme at Malaysia palm oil mill. *European Journal of Scientific Research. ISSN*.

Leading producers of palm oil worldwide from 2020/2021 . (2021). Retrieved from Statista: https://www.statista.com/statistics/856231/palm-oil-top-global-producers/

OEE (Overall Equipment Effectiveness). (2021). Retrieved January 12, 2021, from LEANPRODUCTION: https://www.leanproduction.com/oee/

Melton, T. (2005). The Benefits of Lean Manufacturing: What Lean Thinking has to Offer the Process Industries. *Chemical Engineering Research and Design*, 83(6), pp. 662-673.

Miller, J. (2021, July 22). *TPM Metrics & Financial Impact*. Retrieved from GEMBA ACADEMY: https://blog.gembaacademy.com/2004/11/17/tpm_metrics_financial_impact/

Moubray, J. (2000). FLM to select suitable maintenance strategy in process industries using MISO model. *Journal of Quality in Maintenance Engineering, 11*(4), pp. 359- 374.

Moubray, J. (2003). 21st century maintenance organization part I: the asset management model. *Maintenance technology*, 16(2)

Nakajima, S. (1989). *TPM development program: Implementing total productive maintenance*. Productivity Press.

Nakiyadeniya Oil Palm Mill. (2013, June 6). Retrieved January 24, 2021, from Watawala Plantations: http://nakiyadeniya.blogspot.com/

Naim, A. (2009, December 2). *Preventive Maintenance in Palm Oil Mill* . Retrieved from Palm Oil Mill Preventive Maintenance manual : http://preventivemaintenancepom.blogspot.com/

Noon, M., Jenkins, S., & Lucio, M. M. (2000). Fads, techniques and control: The competing agendas of TPM and TECEX at the Royal Mail (UK). *Journal of Management Studies, 37*(4), pp. 499-519.

OEE (Overall Equipment Effectiveness). (2021). Retrieved January 12, 2021, from LEANPRODUCTION: https://www.leanproduction.com/oee/

Oil room . (2015, October 3). Retrieved from Sharing station: http://limyihang.blogspot.com/2015/10/oil-room.html

Ozbun, A. (2021, May 24). Codex. Retrieved from Unit Root In Time Series: https://medium.com/codex/unit-root-in-time-series-38d451d742ce

Palm Oil Mill SCADA. (2017). Retrieved January 31, 2021, from I-Max Automation Sdn Bhd: https://www.imax-automation.com/scada.html

Palm Oil. (2021). Retrieved from Watawala Plantations Plc: https://watawalaplantations.lk/businesses/palm-oil/

Pintelon, L., & Gelders, L. (1992). Maintenance management decision making. *European Journal of Operational Research, 58*, pp. 301-317.

Pomorski, T.R. (2004). Total productive maintenance (TPM) concepts and literature review. *Brooks Automation, Inc*, 30.

Process Analysis. (2010). Retrieved from NetMBA: http://www.netmba.com/operations/process/analysis/

Ratnasari, D., Nazir, F., Toresano, L., & Pawiro, S. A. (2016, March). The correlation between effective renal plasma flow (ERPF) and glomerular. doi:DOI: 10.1088/1742-6596/694/1/012062

Sangameshwran, P., & Jagannathan, R. (2002). Eight pillars of TPM. *Indian Management, 11*, pp. 36-37.

Shamsuddin, A., Masjuki, H. & Zahari, T. (2004). State of implementation of TPM in SMIs: a survey study in Malaysia. *Journal of Quality in Maintenance Engineering*, 10(2).

Sharma, R. K., Kumar, D., & Kumar, P. (2005). FLM to select suitable maintenance strategy in process industries using MISO model. *Journal of Quality in Maintenance Engineering*, 11(4), pp. 359-374.

Sheu, C., & Krajewski, L. J. (1994). A decision model for corrective maintenance. *International Journal of Production Research*, 32(6), pp.1365-1382.

Shirose, K. (1995). *TPM team guide*. Portland, OR: Productivity Press.

Siregar, A.R., Purba, H.H. & Aisyah, S. (2017). Measuring Overall Equipment Effectiveness (OEE) palm oil mill in Indonesia. *International Journal of Recent Trends in Engineering and Research*.

Sivasothy, K. & Ramachandran, B. (2010). *Process for extracting palm oil using evaporation*. International, Patent No WO 2010/101454 A2.

Slack, N., & Lewis, M. (2008). Operations Strategy. Harlow: Pearson Education Limited.

Tajiri, M. & Gotoh, F. (1992). *TPM implementation, a Japanese approach*. McGraw-Hill Companies.

Toomey, G. (2006). Harnessing the power of maintenance. *Power Engineering, 110*(3), pp. 42-49.

Trout, J. (2021). *What Is Overall Equipment Effectiveness (OEE)?* (N. Corporation, Producer)

Retrieved from https://www.reliableplant.com/Read/11785/overall-equipment-effectiveness

Tsang, A. (1995). Condition-based maintenance: Tools and decision making. *Journal of Quality in Maintenance Engineering,* 1(3), pp. 3-17.

Tsang, H. C. A. (2002). Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering*, 8(1), 7-39.

Tsigkas A. (2013). *The lean enterprise*. Berlin, Heidelberg: Springer Berlin Heidelberg

Venkatesh, J. (2006). An introduction to total productive maintenance. *Malaysia Labour Review 2009,* 3(2).

Wai-Lin, S. (2021). *Palm Oil*. (The American Oil Chemists' Society) Retrieved from https://lipidlibrary.aocs.org/edible-oil-processing/palm-oil

Weber, A. & Thomas, R. (2005). Key performance indicators. *Measuring and Managing the Maintenance Function, Ivara Corporation, Burlington*.

Willmott, P. (1994). Total quality with teeth. *The TQM Magazine*, 6(4), pp.48-50.

Womack, J, P. & Jones, D, T. (2003). *Lean Thinking: Banish Wastes and Create Wealth in your Corporation.* London: Simon & Schuster.

Yang, Y., Liang, S., & Danyluk, S. (1999). Application of a specialized capacitance probe in bearing diagnosis. *Wear*, *225*(2), pp. 1215-1221.

GSJ: Volume 10, Issue 4, April 2022
ISSN 2320-9186

Annex 1: January 2021 OEE calculation

Month-January Date	FFB Processing Capacity(tons/hr)	Total Mill Hours Worked (Up-time/operating time) mins	Mill Breakdown time Reported (mins)	Start up & minor stop (mins)	Total Mill Downtime (mins)	FFB Processed(tons)	CPO Produced (Good Quality) tons	Oil Extraction Rate (OER)	CPO Production Per Hour	Bad Quality CPO Produced (tons)	Availability Rate=Operating Time/(Operating Time+Downtime)	Performance Rate=CPO Produced/CPO Could be produced	Quality Rate=Good CPO/(Good CPO+Bad CPO)	OEE	Availability Loss time	Performance Loss time	Net operating time	Value added time
1	14	990	200	90	290	228	52.44	0.23	3.22	10.20	0.77	0.76	0.84	0.49	290	302.86	687.14	575.25
2	14	880	230	90	320	230	56.3	0.24	3.43	8.10	0.73	0.82	0.87	0.53	320	214.29	665.71	581.98
3	14	993	198	87	285	218	51.23	0.24	3.29	10.10	0.78	0.73	0.84	0.47	285	343.71	649.29	542.36
4	14	850	223	90	313	228	56.34	0.25	3.46	9.30	0.73	0.84	0.86	0.53	313	185.86	664.14	570.05
5	14	986	199	93	292	228	51.33	0.23	3.15	11.00	0.77	0.76	0.82	0.49	292	300.86	685.14	564.23
6	14	875	197	98	295	228	50.33	0.22	3.09	9.20	0.75	0.84	0.85	0.53	295	192.86	682.14	576.72
7	14	990	200	90	290	232	49.35	0.21	2.98	8.30	0.77	0.78	0.86	0.51	290	285.71	704.29	602.89
8	14	896	184	98	282	219	48.99	0.22	3.13	8.90	0.76	0.80	0.85	0.51	282	239.43	656.57	555.63

GSJ: Volume 10, Issue 4, April 2022
ISSN 2320-9186

9	14	982	222	89	311	219	49.22	0.22	3.15	10.20	0.76	0.73	0.83	0.46	311	354.43	627.57	519.84
10	14	986	232	98	330	218	52.44	0.24	3.37	11.20	0.75	0.71	0.82	0.44	330	381.71	604.29	497.94
11	14	896	198	111	309	215	53.24	0.25	3.47	11.10	0.74	0.76	0.83	0.47	309	283.57	612.43	506.77
12	14	852	199	95	294	216	51.39	0.24	3.33	9.30	0.74	0.81	0.85	0.51	294	220.29	631.71	534.91
13	14	896	215	89	304	222	51.37	0.23	3.24	5.30	0.75	0.79	0.91	0.54	304	248.57	647.43	586.88
14	14	953	223	87	310	228	52.44	0.23	3.22	5.80	0.75	0.77	0.90	0.53	310	285.86	667.14	600.70
15	14	863	198	56	254	226	51.37	0.23	3.18	5.90	0.77	0.87	0.90	0.60	254	148.43	714.57	640.96
16	14	987	216	86	302	219	49.38	0.23	3.16	6.40	0.77	0.73	0.89	0.49	302	350.43	636.57	563.53
17	14	968	196	58	254	209	48.38	0.23	3.24	6.90	0.79	0.73	0.88	0.51	254	326.29	641.71	561.62
18	14	999	219	89	308	239	51.43	0.22	3.01	9.50	0.76	0.78	0.84	0.51	308	282.71	716.29	604.60
19	14	859	228	96	324	223	52.44	0.24	3.29	9.60	0.73	0.81	0.85	0.50	324	227.29	631.71	533.96
20	14	953	225	84	309	211	52.54	0.25	3.49	8.60	0.76	0.72	0.86	0.46	309	357.71	595.29	511.55
21	14	986	198	75	273	215	51.29	0.24	3.34	11.30	0.78	0.73	0.82	0.47	273	337.57	648.43	531.36
22	14	876	219	90	309	216	51.87	0.24	3.36	10.90	0.74	0.78	0.83	0.48	309	259.29	616.71	509.62
23	14	854	220	56	276	218	50.29	0.23	3.23	11.80	0.76	0.83	0.81	0.51	276	195.71	658.29	533.18
24	14	891	218	94	312	217	52.78	0.24	3.41	10.20	0.74	0.77	0.84	0.48	312	273.00	618.00	517.91
25	14	863	214	87	301	222	52.44	0.24	3.31	12.30	0.74	0.82	0.81	0.49	301	212.57	650.43	526.85
26	14	845	199	85	28	22	52.1	0.2	3.2	10.8	0.75	0.87	0.83	0.54	28	151.8	693.14	574.30

					4	8	9	3	0	0					4	6		
27	14	879	200	82	28 2	21 9	52.1 6	0.2 4	3.3 3	10.2 0	0.76	0.81	0.84	0.51	28 2	222.4 3	656.57	549.18
28	14	895	211	90	30 1	21 3	52.3 4	0.2 5	3.4 4	12.3 0	0.75	0.76	0.81	0.46	30 1	283.1 4	611.86	495.43
29	14	876	216	98	31 4	22 6	51.2 7	0.2 3	3.1 8	9.30	0.74	0.81	0.85	0.51	31 4	221.4 3	654.57	554.07
30	14	986	192	99	29 1	22 8	52.4 4	0.2 3	3.2 2	8.30	0.77	0.77	0.86	0.51	29 1	299.8 6	686.14	592.38
31	14	861	200	95	29 5	22 7	52.1 6	0.2 3	3.2 2	10.2 0	0.74	0.84	0.84	0.52	29 5	183.1 4	677.86	566.98
Total											**23.4 1**	**24.33**	**26.2 4**	**15.5 5**				
Mea n											**0.76**	**0.78**	**0.85**	**0.50**				

Annex 2: February 2021 OEE calculation

Month-February Date	FFB Processing Capacity(tons/hr)	Total Mill Hours Worked (Up-time/operating time) mins	Mill Breakdown time Reported (mins)	Start up & minor stop (mins)	Total Mill Downtime (mins)	FFB Processed(tons)	CPO Produced (Good Quality) tons	Oil Extraction Rate (OER)	CPO Production Per Hour	Bad Quality CPO Produced (tons)	Availability Rate=Operating Time/(Operating Time+Downtime)	Performance Rate=CPO Produced/CPO Could be produced	Quality Rate=Good CPO/(Good CPO+Bad CPO)	OEE
1	14	989	153	39	192	228	52.44	0.23	3.22	10.50	0.84	0.83	0.83	0.58
2	14	986	159	39	198	230	56.3	0.24	3.43	13.25	0.83	0.83	0.81	0.56
3	14	956	128	37.7	165.7	218	51.23	0.24	3.29	14.56	0.85	0.83	0.78	0.55
4	14	858	189	39	228	228	56.34	0.25	3.46	12.36	0.79	0.90	0.82	0.58
5	14	865	176	40.3	216.3	228	51.33	0.23	3.15	17.56	0.80	0.90	0.75	0.54
6	14	875	176	42.46667	218.4667	228	50.33	0.22	3.09	16.00	0.80	0.89	0.76	0.54
7	14	986	145	39	184	232	49.35	0.21	2.98	12.00	0.84	0.85	0.80	0.58
8	14	953	125	42.46667	167.4667	219	48.99	0.22	3.13	12.36	0.85	0.84	0.80	0.57
9	14	954	148	38.56667	186.5667	219	49.22	0.22	3.15	12.50	0.84	0.82	0.80	0.55
10	14	986	123	42.46667	165.4667	218	52.44	0.24	3.37	12.60	0.86	0.81	0.81	0.56
11	14	932	125	48.1	173.1	215	53.24	0.25	3.47	14.00	0.84	0.83	0.79	0.56
12	14	876	145	41.16667	186.1667	216	51.39	0.24	3.33	15.00	0.82	0.87	0.77	0.56
13	14	896	145	38.56667	183.5667	222	51.37	0.23	3.24	17.00	0.83	0.88	0.75	0.55
14	14	867	178	37.7	215.7	228	52.44	0.23	3.22	12.30	0.80	0.90	0.81	0.59
15	14	824	169	24.26667	193.2667	226	51.37	0.23	3.18	15.00	0.81	0.95	0.77	0.60
16	14	846	202	37.26667	239.2667	219	49.38	0.23	3.16	19.00	0.78	0.86	0.72	0.49
17	14	862	124	25.13333	149.1333	209	48.38	0.23	3.24	12.80	0.85	0.89	0.79	0.60
18	14	875	145	38.56667	183.5667	239	51.43	0.22	3.01	15.60	0.83	0.97		0.61

GSJ: Volume 10, Issue 4, April 2022
ISSN 2320-9186

19	14	896	102	41.6	143.6	223	52.44	0.24	3.29	14.00	0.86	0.92	0.79	0.63
20	14	875	105	36.4	141.4	211	52.54	0.25	3.49	15.00	0.86	0.89	0.78	0.60
21	14	862	104	32.5	136.5	215	51.29	0.24	3.34	17.00	0.86	0.92	0.75	0.60
22	14	956	108	39	147	216	51.87	0.24	3.36	19.00	0.87	0.84	0.73	0.53
23	14	896	109	24.26667	133.2667	218	50.29	0.23	3.23	12.50	0.87	0.91	0.80	0.63
24	14	843	136	40.73333	176.7333	217	52.78	0.24	3.41	14.60	0.83	0.91	0.78	0.59
25	14	876	145	37.7	182.7	222	52.44	0.24	3.31	18.60	0.83	0.90	0.74	0.55
26	14	876	125	36.83333	161.8333	228	52.19	0.23	3.20	19.50	0.84	0.94	0.73	0.58
27	14	826	178	35.53333	213.5333	219	52.16	0.24	3.33	14.30	0.79	0.90	0.78	0.56
28	14	849	179	39	218	213	52.34	0.25	3.44	15.30	0.80	0.86	0.77	0.53
29	14	819	145	42.46667	187.4667	226	51.27	0.23	3.18	14.50	0.81	0.96	0.78	0.61
30	14	896	169	42.9	211.9	228	52.44	0.23	3.22	12.80	0.81	0.88	0.80	0.57
31	14	876	127	41.16667	168.1667	227	52.16	0.23	3.22	12.50	0.84	0.93	0.81	0.63
Total											**25.74**	**27.44**	**24.18**	**17.76**
Mean											**0.83**	**0.89**	**0.78**	**0.57**

Annex 3: OEE calculation (2017-2020)

From 2017 to 2020	FFB Processing Capacity(tons/hr)	Total Mill Hours Worked (Up-time/operating time) mins	Mill Breakdown time Reported (mins)	Start up & minor stop (mins)	Total Mill Downtime (mins)	FFB Processed(tons)	CPO Produced (Good Quality) tons	Oil Extraction Rate (OER)	CPO Production Per Hour	Bad Quality CPO Produced (tons)	Availability Rate=Operating Time/(Operating Time+Downtime)	Performance Rate=CPO Produced/CPO Could be produced	Quality Rate=Good CPO/(Good CPO+Bad CPO)	OEE
January	14	66324	6496	7516	14012	13416	3354	0.25	3.50	56.00	0.83	0.72	0.98	0.58
February	14	67580	6748	7584	14332	13828	3595.28	0.26	3.64	44.00	0.83	0.72	0.99	0.59
March	14	67948	6448	5284	11732	13816	3454	0.25	3.50	100.00	0.85	0.74	0.97	0.62
April	14	67428	4980	4536	9516	13296	3191.04	0.24	3.36	68.00	0.88	0.74	0.98	0.64
May	14	86348	15156	12500	27656	19684	4133.64	0.21	2.94	416.00	0.76	0.74	0.91	0.51
June	14	86356	15424	12016	27440	19996	3999.2	0.20	2.80	432.00	0.76	0.75	0.90	0.52
July	14	86272	15516	8668	24184	18792	4698	0.25	3.50	428.00	0.78	0.73	0.92	0.52
August	14	85956	15516	8616	24132	18740	4310.2	0.23	3.22	340.00	0.78	0.73	0.93	0.53
September	14	86188	14796	10312	25108	19468	4282.96	0.22	3.08	640.00	0.77	0.75	0.87	0.51
October	14	86192	13424	10632	24056	19032	4758	0.25	3.50	432.00	0.78	0.74	0.92	0.53
November	14	87584	15584	10220	25804	19584	4112.64	0.21	2.94	428.00	0.77	0.74	0.91	0.52
December	14	89832	15156	11872	27028	19428	4274.16	0.22	3.08	456.00	0.77	0.71	0.90	0.49

GSJ: Volume 10, Issue 4, April 2022
ISSN 2320-9186

Annex 4: OEE values for other Malaysian mills

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ABZ	0.5587	0.5746	0.6258	0.6789	0.5023	0.5078	0.5069	0.5489	0.5321	0.4987	0.4687	0.4698
Johor	0.689	0.6896	0.6456	0.6987	0.7025	0.7145	0.7258	0.6987	0.6897	0.6896	0.6856	0.7023
Kedah	0.8021	0.812	0.7965	0.7963	0.8276	0.7967	0.7896	0.8246	0.8148	0.7569	0.7469	0.7215
Melaka	0.7896	0.7521	0.7158	0.7458	0.6989	0.689	0.7021	0.7568	0.678	0.625	0.786	0.758
Pahang	0.6989	0.658	0.648	0.702	0.701	0.713	0.6869	0.678	0.658	0.701	0.659	0.623
Sabah	0.789	0.785	0.759	0.715	0.718	0.698	0.695	0.702	0.745	0.749	0.718	0.713

Annex 5: Loss time calculation

From 2017 to 2020	Total Mill Hours Worked (Up-time/operating time) mins	Mill Breakdown time Reported (mins)	Total Mill Downtime (mins)	Availability Rate=Operating Time/(Operating Time+Downtime)	Performance Rate=CPO Produced/CPO Could be produced	Quality Rate=Good CPO/(Good CPO+Bad CPO)	OEE	Availability Loss Time	Performance Loss Time	Net Operating Time	Quality Loss Time	Value Added Time
January	66324	6496	14012	0.83	0.72	0.98	0.58	14012	22838.86	43485.14	714.13	42771.02
February	67580	6748	14332	0.83	0.72	0.99	0.59	14332	22649.14	44930.86	543.23	44387.63
March	67948	6448	11732	0.85	0.74	0.97	0.62	11732	20468.57	47479.43	1335.94	46143.49
April	67428	4980	9516	0.88	0.74	0.98	0.64	9516	19961.14	47466.86	990.40	46476.46
May	86348	15156	27656	0.76	0.74	0.91	0.51	27656	29644.00	56704.00	5184.78	51519.22
June	86356	15424	27440	0.76	0.75	0.90	0.52	27440	28098.86	58257.14	5679.52	52577.62
July	86272	15516	24184	0.78	0.73	0.92	0.52	24184	29918.86	56353.14	4705.26	51647.89
August	85956	15516	24132	0.78	0.73	0.93	0.53	24132	29773.71	56182.29	4107.78	52074.51
September	86188	14796	25108	0.77	0.75	0.87	0.51	25108	27861.71	58326.29	7582.60	50743.69
October	86192	13424	24056	0.78	0.74	0.92	0.53	24056	28682.29	57509.71	4786.94	52722.78
November	87584	15584	25804	0.77	0.74	0.91	0.52	25804	29456.57	58127.43	5479.08	52648.35
December	89832	15156	27028	0.77	0.71	0.90	0.49	27028	33597.14	56234.86	5421.19	50813.67

Annex 6: Unit root analysis data