Department of Management and Production Engineering

Master's Thesis in Engineering and Management

Analysis of Overall Equipment Effectiveness (OEE)

in Solar Panel Manufacturing

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TABLE OF CONTENTS

ABSTRACT

In today's competitive manufacturing landscape, the sustainability and profitability of enterprises hinge on optimizing production efficiency and reducing industrial waste. ENTER SOLAR GREEN ENERGY exemplifies this challenge, striving to improve its product offerings by identifying and eliminating non-value-added processes. This thesis explores how Overall Equipment Effectiveness (OEE) can be utilized to identify inefficiencies and boost productivity within the company as an effective diagnostic tool .

By examining both the theory and real-world application of OEE, this research evaluates the manufacturing performance of ENTER SOLAR GREEN ENERGY. Together with

quantitative and qualitative data collection methods, we used key metrics including availability, performance, and quality.

Our results show that there are many potential opportunities for improvement in process optimization and equipment maintenance. One important strategy for eliminating six different types of avoidable waste and improving the performance of overall equipment is Total Productive Maintenance (TPM). The thesis also addresses the challenges of data collection and waste classification, highlighting the importance of customized solutions in order to meet the demands of the sector.

By treating OEE as a stochastic variable and employing approximate statistical techniques, the study provides a robust framework for analyzing production variability and identifying root causes of inefficiencies. This approach facilitates data-driven decision-making, leading to more effective and efficient manufacturing processes.

The practical implications of this research extend to improving asset reliability, prioritizing improvement efforts, and monitoring equipment efficiency over time. The study underscores the importance of collaborative efforts across operations, maintenance, procurement, and system design to achieve sustainable improvements in manufacturing performance.

In conclusion, this thesis demonstrates the value of OEE as a comprehensive metric for enhancing manufacturing efficiency and competitiveness. It offers actionable insights and methodologies for ENTER SOLAR GREEN ENERGY and similar enterprises to optimize their production processes, reduce costs, and meet market demands more effectively.

1. INTRODUCTION

In recent decades, manufacturing enterprises have grappled with the looming threat of market exit due to waning customer retention. To counter this, there is an urgent imperative to curtail industrial waste while enhancing production efficiency. Rather than resorting to price hikes that could strain customer relations, manufacturers are increasingly focused on trimming operational costs and bolstering economic efficiency.

The formula representing total profit TP = P * Q - TC underscores the interplay between price (P), quantity (Q), and total cost (TC) of a product. Adjusting either the price or the cost structure can yield heightened profitability. However, prioritizing cost reduction is critical, as excessive price hikes may alienate customers. Manufactures can improve the output of production while reducing maintenance expenses through the implementation of Total Productive Maintenance (TPM). TPM serves as a holistic framework for identifying and mitigating six distinct forms of preventable waste within manufacturing processes.

Problem Statement

As ENTER SOLAR GREEN ENERGY strives to improve its product offerings, identifying and eliminating non-value-adding processes becomes imperative to maximizing productivity. Using Overall Equipment Effectiveness (OEE), it becomes possible to identify inefficiencies related to system functionality and quality, thereby identifying these processes as sources of waste. Conducting a thorough OEE performance study is crucial for uncovering potential losses and understanding how they impact the various variables of OEE.

However, challenges often arise in data collection for OEE studies and in adapting the loss categorization framework to suit the unique requirements of the industry. A recent study by

Muchiri and Pintelon offers a comprehensive literature review on these challenges, highlighting the need for innovative solutions to address them effectively.

Aims and Research Questions

This thesis aims to explore the benefits of OEE by delving into its theoretical underpinnings. Within the realm of OEE literature, performance evaluation holds significant importance. The study proceeds to analyze OEE measurements and associated losses within ENTER SOLAR GREEN ENERGY, showcasing the practical application of the OEE methodology, which enables departments within a company to schedule and monitor changes effectively.

In light of these considerations, it becomes apparent that OEE calculations should incorporate volatility analysis. Beginning with the primary determinants of waste's Probability Density Function (PDF), OEE is treated as a stochastic random variable, and an approximate statistical technique is employed to establish its PDF. This approach streamlines the selection of an appropriate data collection period, facilitating the analysis of OEE's mean and standard deviation (i.e., variability). Data consolidation for OEE can be conducted on a monthly or quarterly basis, for instance, with the plant's operating lifecycle serving as the suitable timeframe for data collection. This ensures the reliability and robustness of outcomes while retaining essential information about production variability.

Furthermore, the proposed methodology offers the opportunity to detect and evaluate the impact of different remedial measures from the point of view of both efficiency and efficacy, presenting a significant advantage. It is widely acknowledged that a manufacturing process is deemed successful if it achieves desired results and efficient if it does so with minimal resources. Rather than solely focusing on outputs to gauge process effectiveness, efficiency assesses inputs to determine how well a process operates.

Research Question

- Is OEE a commonplace occurrence?
- Example: OEE stands at 85 percent, comprising 90 percent availability, 95 percent performance, and 99.9 percent quality.

Objectives of OEE

- To enhance the overall performance and reliability of an asset by concentrating on a specific machine or equipment piece.
- To serve as a starting point for prioritizing improvement efforts and identifying root causes in instances of underperformance or failure to meet expectations.
- To monitor the progression or regression of equipment efficiency over time.
- To prevent an imbalanced flow by leveraging or concealing unused industrial capacity.

Given that "maintenance" alone cannot singularly improve OEE, collaborative efforts across asset operations, maintenance, procurement, and system design are essential to identify and mitigate (or minimize) the root causes of poor performance.

Project Limitations

Scope of evaluation: The tool can only evaluate the machine's overall performance. For this study, data collection from sources outside the specified plant was irregular. As a result, some data sets were insufficient for a comprehensive evaluation, while others could not be processed.

Time Limitations: The results of this dissertation study may be affected by significant differences in product requirements and equipment limitations observed in the data collected over a three-month period (March and April 2023). Additionally, it is still unclear how complex product designs and operator skills affect OEE results, requiring further research.

2. BACKGROUND

Nowadays, in a highly competitive market, it is crucial to maximise efficiency and effectiveness to increase output across industries. Success is now measured primarily by profitability growth, which requires careful attention to identifying and eliminating hidden waste and bottlenecks in manufacturing environments. This entails the adoption of performance metrics that measure equipment performance against its theoretical capacity.[2].

It has been observed through industry analysis that there's a pressing need for recalibrating performance evaluations or employing appropriate metrics accurately [3]. To this end, two critical considerations emerge: what to measure and how to measure it. Sustaining competitiveness in manufacturing hinges on optimizing production facilities to ensure they remain both available and productive [4]. This suggests that increasing efficiency—which involves reducing preventable production losses—should be the main priority. Customer satisfaction, competitiveness, and production costs are all improved by such initiatives [5].

The Japan Institute of Plant Maintenance (JIPM) was the first to introduce the TPM concept, which has since spread throughout many industries. It is the foundation of approaches to productivity enhancement like lean manufacturing and total quality management (TQM). Nakajima's introduction of the term "total productive maintenance" (TPM) laid the groundwork for "overall equipment effectiveness" (OEE), which facilitates the identification and quantification of a company's most efficient machinery [6]. OEE comprises three crucial assessment components: performance, availability, and quality. Real-time monitoring capabilities enable swift identification and rectification of potential losses, thereby enhancing productivity across equipment, personnel, and materials.

OEE's implementation has yielded significant benefits across diverse industries. Notably, in semiconductor manufacturing, it has bolstered equipment efficiency and expanded productivity [5]. In Nigeria's beverage sector, its adoption resulted in a 50% surge in value and a reduction in waste, accompanied by increased equipment uptime [7]. Moreover, Airbags International Ltd.'s (AIL) integration of OEE as a primary production metric unveiled new levels of performance measurement [10]. Despite scholarly acknowledgment of OEE's depth, its practical application across various domains remains largely unexplored, highlighting avenues for further research and implementation.

OEE serves as both a benchmark and a yardstick for evaluating performance [10]:

- **Benchmarking against Industry Standards:** OEE enables the assessment of an output resource against established industry benchmarks. Alternatively, it can be compared with similar in-house assets or with the performance of various shifts operating the same asset.
- **Baseline for Progress Measurement:** OEE also functions as a baseline to gauge advancements in minimizing inefficiencies over time on a particular production asset.

2.1. OEE Benchmarking

- **"Good" OEE Score:** Producing high-quality components consistently at maximum speed without any downtime interruptions results in a perfect OEE score of 100%.
- **World-Class OEE Score:** Independent manufacturers consider an OEE of 85% world-class. Achieving this level is a significant milestone and a long-term goal for many businesses.

- **Benchmark OEE Score:** A baseline OEE score of 60% is considered good, indicating reasonable efficiency levels. However, there is ample room for improvement within this industry segment.
- **Starting Point for New Manufacturers:** For newly established manufacturing companies, attaining a 40% OEE score is not uncommon. While it may initially seem low, simple measures such as documenting stoppage causes and systematically addressing primary sources of downtime can incrementally enhance performance. Nonetheless, this score suggests ample room for improvement and signifies a suboptimal operational grade.

3. TOTAL PRODUCTIVE MAINTENANCE (TMP) AND OVERALL EQUIPMENT EFFECTIVENESS (OEE)

3.1. Total Productive Maintenance

In Total Productive Maintenance (TPM), machine operators play a hands-on role in preventing downtime caused by equipment defects, waste, energy losses, and labor productivity inefficiencies. Using Overall Equipment Effectiveness (OEE), TPM helps identify and reduce these losses by measuring efficiency based on availability, productivity, and quality.

3.1.1. Historical Context

In an ideal factory, every machine would operate at peak efficiency, producing high-quality products without interruption. But in reality, there are many problems that affect productivity. To address these issues, the Japan Institute of Plant Maintenance (JIPM) introduced Total Production Management (TPM) in 1971, a comprehensive approach designed to improve production efficiency by improving equipment performance. The Japanese model, which calculates OEE, originated from the efficient production systems developed by Toyota and others in the early 1930s, inspired by Henry Ford's production line model. Following World War II, Japan's economy faced severe challenges, leading to the need for operational optimization. Total system efficacy measurement helps identify potential equipment losses.

3.1.2. Benefits of Measurement

As highlighted by Ljungberg & Larsson [21], measurements serve various crucial purposes and offer numerous benefits:

1. **Understanding Effort-to-Outcome Correlations:** Measurement enables a clear understanding of how different levels of effort translate into specific outcomes. This correlation helps in assessing the effectiveness of various strategies and processes.
2. **Facilitating Communication:** Establishing a common language through measurement allows for better communication among team members, departments, and stakeholders. This shared understanding is essential for collaborative efforts and alignment of goals.
3. **Acting as a Powerful Motivator:** Measurement serves as a powerful motivator by providing concrete evidence of progress and success. When individuals and teams see tangible results from their efforts, it can boost morale and drive further improvement.
4. **Tracking Long-Term Progress:** Consistently tracking numbers is vital for understanding long-term progress. It helps organizations monitor trends, evaluate the effectiveness of interventions over time, and make informed decisions based on historical data.
5. **Driving Improvement:** Measuring things helps identify what needs improvement. Tracking performance makes it easier to identify gaps and make meaningful changes. It builds a culture of ongoing improvement, where decisions are based on actual data rather than guesswork.
6. **Assisting in Delegation:** Explicit measures of success are essential for effective delegation. When people know precisely what is expected of them, they can confidently take ownership of their work, leading to better results and less confusion.
7. **Identifying Problems:** Problems and inefficiencies can be identified through measurement. Organisations can pinpoint issues and address them by analysing performance data before they escalate.

8. **Focusing Managerial Attention:** Measurements help focus managerial attention on critical areas. Managers can prioritize their efforts and resources on the most impactful activities, ensuring efficient use of time and energy.
9. **Enabling Comparisons:** Comparisons within and across different units, departments, or time periods become possible through measurements. This benchmarking is crucial for understanding relative performance and identifying best practices.
10. **Aiding in Future Planning:** Measurement aids in future planning by providing a solid foundation of data. It helps in setting realistic goals, forecasting needs, and developing strategic plans based on empirical evidence.
11. **Answering Questions about Production:** Measurement provides answers to key questions about "where" and "whither" in the context of production. It helps determine the current state and the direction in which the organization needs to move to achieve its objectives.

Overall Equipment Effectiveness (OEE) finds application in various stages of production, serving as a benchmark for companies to enhance decision-making and improve overall performance [22]. By utilizing OEE, organizations can comprehensively evaluate their equipment efficiency, identify areas for improvement, and implement strategies to maximize productivity and quality. This systematic approach ensures that production processes are continuously optimized, contributing to the organization's long-term success and competitiveness.

3.1.3. TPM concept

TPM (Total Productive Maintenance), a Japanese concept, provides an alternative to the US-based preventative maintenance approaches by focusing on "total productivity" and fitting well within industrialized environments. The creator of TPM introduced the idea of task grouping to enhance efficiency through maintenance, which involves operators working collaboratively.

Brah and Chong [23] highlight that reducing waste and pursuing continuous improvement necessitates collaboration between workers and managers. In the TPM framework, maintenance teams are responsible for all manufacturing repairs, which streamlines the distribution of tasks. With complete employee dedication and participation, it is possible to minimize disruptions during operations. The goal is to achieve zero downtime, accidents, faults, dust, and dirt before implementing TPM.

3.1.4. Key elements of TPM

3.1.4.1. Total

- Involvement of every employee fosters problem-solving attitudes through awareness and information dissemination. Both management and the entire team must collaborate to achieve this (top management).
- Focus on eliminating errors, malfunctions, and breakdowns.
- Completion of various tasks during the manufacturing process, leading to fewer problems.
- Consistent meeting or surpassing customers' expectations for the final product or service during production.

3.1.4.2. Productive

- The manufacturing process involves the completion of various duties.
- Fewer problems are encountered during manufacturing.
- Production aims to consistently meet or exceed customers' expectations for the final product or service.

3.1.4.3. Maintenance

- Maintenance is the process of returning machinery or equipment to its original state, hence extending its lifespan.
- Repairing worn-out or broken components, as well as cleaning or lubricating, are all part of the job.

3.1.5. Eight-Pillar Approach for TPM Implementation

Ahuja [24] proposed an eight-pillar strategy for TPM implementation, drawing from the TPM pillar efforts of the Japan Institute of Plant Maintenance (JIPM).

3.1.5.1. Development management

- Ensure smooth and timely operation with minimal issues when implementing new equipment.
- Innovate new systems based on insights gained from current systems.
- Undertake projects aimed at enhancing maintenance processes.

3.1.5.2. Office TPM

- Simplify various business processes to improve efficiency.
- Eliminate bureaucratic hurdles to streamline operations.

- Focus on resolving cost-related issues.
- Implement the 5S method in office spaces to enhance organization and cleanliness.

3.1.5.3. Safety, health, and the environment

- Establish and maintain a safe working environment.
- Create a conducive working environment that promotes well-being.
- Prevent incidents of injuries and accidents.
- Provide access to standard operating procedures for safety protocols.

3.1.5.4. Education and training

- Provide education and training in technical skills, quality assurance, and interpersonal talents.
- Encourage multitasking among employees in order to extend their skill sets.
- Align organisational aims with the goals of employees.
- Conduct periodic skill assessments to verify that your skills are up to date.

3.1.5.5. Quality maintenance

- Eliminate all errors to achieve high-quality results.
- Determine and treat the root causes of machine breakdowns.
- Implement a 3M (Machine/Man/Material) system to improve operations.

3.1.5.6. Planned maintenance

- Ensure equipment longevity through strategic long-term planning and Total Productive Maintenance (TPM) systems.
- Develop project management checklists to facilitate planned maintenance activities.

- Improve Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) to enhance equipment reliability. ->reference?

3.1.5.7. Focused improvement

- Systematically identify and eliminate the 16 types of losses to improve overall efficiency.
- Conduct structured why-why and Failure Mode and Effects Analysis (FMEA) analyses to identify and reduce loss factors.
- Aim to achieve enhanced system efficiency and improved Overall Equipment Effectiveness (OEE) in the production system.

3.1.5.8. Autonomous maintenance

- Foster a sense of personal ownership among operators.
- Empower operators to perform tasks such as cleaning, lubricating, tightening, adjusting, and examining manufacturing equipment autonomously.
- Encourage proactive maintenance actions and empower operators to make necessary adjustments as needed to ensure optimal equipment performance.

3.2. Overall Equipment Effectiveness (OEE)

"Overall Equipment Effectiveness" (OEE), coined by Seiichi Nakajima in the 1980s, was designed to measure machine productivity in production settings [11]. Over time, OEE has become popular because it helps identify and evaluate hidden or unnecessary costs related to specific equipment [6]. While every industry strives for top-quality products and full capacity, achieving these improvements depends on accurate measurements.

OEE is a widely recognized concept in maintenance practices and serves as a tool for monitoring equipment efficiency. However, practical implementation can be challenging due to various factors affecting equipment performance. These factors can lead to diminishing returns with increased utilization, creating a gap between the equipment's original condition and its current state due to losses.

3.2.1. OEE definition

Seiichi Nakajima first proposed the idea of Overall Equipment Effectiveness (OEE) in the 1980s as a component of the Total Productive Maintenance (TPM) framework. One important indicator for evaluating and reducing production losses associated with equipment efficiency is OEE.

Organisations, particularly senior management, use OEE to monitor performance over time, frequently comparing current levels to historical benchmarks to discover areas for improvement. Nakajima discovered six major causes of output loss: equipment breakdowns, setup and adjustment delays, idle and minor stoppages, lower operating speed, quality faults, and rework.

However, these six categories do not include all possible elements that influence efficiency. Other factors, such as scheduled downtime, labour shortages, or external interruptions, can all have an impact on operational performance and should be factored into a larger efficiency analysis.

3.2.2. Optimal OEE Values

Nakajima specified optimal OEE values, with a benchmark of 85 percent considered "world-class." This consists of an availability rate of 90 percent, performance rate of 95 percent, and quality rate of 99 percent. While some researchers suggest a minimum OEE benchmark of over 50 percent, others propose values ranging from 60% to 75% or even 30%

to 80%. Empirical studies have shown varied OEE values, with one study reporting an average OEE of 55% and availability of 80%, closely aligning with Nakajima's claim.

However, there are disparities in performance rates, with empirical data often falling significantly below Nakajima's suggested 95 percent. Factors such as idling and small stoppage losses contribute to lower performance rates, while accessibility losses are significant contributors to overall losses. Quality rates, on the other hand, tend to align more closely with Nakajima's predictions, often reaching 99 percent in empirical studies.

3.2.3. The purpose of OEE

Any performance of a manufacturing facility can be evaluated and enhanced using Overall Equipment Effectiveness (OEE). This evaluation, which offers a comprehensive picture of production efficiency, can be carried out at several organizational levels. Organizations can monitor their improvement and identify areas for advancement by comparing OEE data from the past and the future [22].

OEE also allows you to compare the performance of multiple production lines in the same industry. Analyzing the OEE importance of a single production line will allow you to locate which units are underperforming and require additional attention [6]. This makes OEE an essential tool for identifying inefficiencies and focusing on specific equipment that needs improvement.

OEE is a basis for process improvement and a measurement tool, and it aids in determining areas of a process that require advancement and is necessary to ensure that equipment performs to its full capacity. A crucial step in the process is determining and resolving issues that hinder optimal performance, which raises productivity and efficiency in the production setting.

3.2.4. Chronic and Sporadic disruptions

The purpose of the OEE measure is to identify inefficiencies that waste resources without contributing value to the machine's output. Jonsson and Lesshammar [2] delineate two types of industrial disruptions responsible for these losses: chronic disturbances and sporadic disturbances.

3.2.4.1. Chronic Disturbances

Chronic disturbances, as defined by Tajiri and Gotoh [25], are characterized as small, hidden issues stemming from concurrent technological causes. These disruptions occur frequently, leading to reduced equipment utilization and increased costs. Chronic problems can be challenging to detect as they often blend into the normal manufacturing process. One approach to identifying chronic disturbances is to compare actual performance against potential performance. Building on Nakajima's (1989) work, these losses can be categorized into evident and concealed losses based on their characteristics.

3.2.4.2. Sporadic Disturbances

Sporadic disruptions are easily identifiable due to their significant deviations from the norm. While they occur infrequently, their impact can be severe when they do occur. Both chronic and sporadic disruptions result in various wasteful outcomes that add no value. To uncover these losses, a bottom-up approach, as suggested by Nakajima (1988), is being employed.

3.2.3. The classification structure of OEE losses

The ratio between actual production and optimal production defines any "E" effectiveness metric, representing the percentage of time equipment operates at its maximum capacity [1].

Mathematically, this concept can be expressed as follows:

$$E = \frac{Actual\ output}{Theoretical\ output} = \frac{(Cycle\ time \times Valuable\ time)}{(Cycle\ time \times Theoretical\ time)} = \frac{Valuable\ time}{Theoretical\ time}$$

Here, Valuable Time refers to the duration during which equipment operates at its peak efficiency, while Theoretical Time denotes the maximum time that can be effectively utilized.

By employing various Theoretical Time values based on the categorization of losses, three effectiveness measures can be derived from the formula above:

- $Net\ utilization = \frac{Valuable\ time}{Operating\ time}$
- $Operation\ effectiveness = \frac{Valuable\ time}{Loading\ time}$
- $Overall\ equipment\ effectiveness = \frac{Valuable\ time}{Net\ loading\ time}$

OEE only encompasses inefficiencies directly attributable to equipment, while Net Utilization accounts for other types of losses. OEE serves as a performance measure intended to complement the efforts of production personnel, such as maintenance operators and production engineers, focusing solely on the efficiency of individual equipment rather than overall factory performance [26]. Net Loading Time is utilized in OEE calculation because it encompasses both internal and external losses that cannot be solely attributed to a single piece of equipment, including blockages, waiting times, and the time required for loading and unloading products (i.e., equipment-independent losses). Although this approach is valid, equipment-independent losses cannot be mitigated through corrective actions confined to a single production system, such as plant layout adjustments, machine balancing, or buffer size adjustments.

$$OEE = \frac{(NLT - DT - PLT - QRT)}{NLT}$$

Where:

- NLT = Net Loading Time
- DT = Downtime
- PLT = Time lost due to Performance Losses
- QRT = Time lost due to Quality Rate

Additionally [1]:

$$OEE = \frac{OpT}{NLT} \times \frac{NOpT}{OpT} \times \frac{VT}{NOpT} = \frac{(NLT-DT)}{NLT} \times \frac{(OpT - PLT)}{OpT} \times \frac{(NOpT - QRT)}{NOpT}$$

$$= \frac{(NLT - DT) * NLT * (MI * CT)}{OpT} \times \frac{DF}{MI} = A \times P \times Q$$

Where:

- OpT = Operating Time
- NOpT = Net Operating Time
- VT = Valuable Time
- MI = Number of Manufactured Items
- CT = Cycle Time
- DF = Number of Defects
- PLT = (OpT / CT – MI) * CT = OpT – MI * CT
- QRT = (MI – DF) * CT

3.2.4. Six big losses

Drawing from the TPM framework, Nakajima [6] introduced OEE as a pivotal metric aimed at achieving equipment operations devoid of breakdowns and defects. This strategic approach not only enhances productivity but also reduces costs and minimizes inventory levels. According to Muchiri and Pintelon [11], TPM is primarily focused on enhancing various facets of industrial equipment, including quality, productivity, cost efficiency, inventory management, safety, and overall manufacturing output [9].

Overall Equipement Effectiveness	**Recommended 6 big losses**	**Traditional 6 big losses**
Availability loss	Unplanned Stops Planned Stops	Equipment Failure Setup and Adjustments
Performance Loss	Small Stops Slow Cycles	Idling and Minor stops Reduced Speed
Quality Loss	Production Rejection Startup rejects	Process Defects Reduced Yield
OEE	Fully Productive Time	Valuable Operating Time

Nakajima (1988) proposed a bottom-up approach to mitigate losses resulting from interruptions in manufacturing processes by addressing six major areas. Drawing insights from his observations while residing in Japan, Nakajima identified the following key conclusions

3.2.4.1. Losses due to unplanned downtime as a function of Availability

1. Losses resulting from unplanned downtime directly impact a machine's availability within the business context. Breakdowns, a common cause of equipment failure,

result in losses of both time and quantity. For instance, Pintelon [11] describes how a malfunctioning motor in a brewery's material handling plant led to production delays and losses.

2. Another significant source of loss is associated with set-up and adjustment, often termed "transitional losses." These occur during shifts in manufacturing from one item to another and include activities such as product set-ups, startup testing, and equipment fine-tuning in the brewing process [27].

Availability = Actual working time / Scheduled working time

3.2.4.2. Speed losses and Performance

1. Speed losses directly affect a machine's overall performance. By eliminating these losses, we can determine the machine's true output potential. However, if the machine breaks down, it becomes impossible to accurately measure or calculate its performance.

These losses manifest when production is momentarily halted, such as during machine idle periods. For instance, in material handling machines, even swift repairs of dirty photocells can lead to minute interruptions, resulting in substantial capacity losses.

Common triggers of these micro stops include:

- Equipment misalignment and improper positioning
- Incorrect settings
- Blocked sensors
- Material miss-feeds and jams
- Equipment design flaws
- Periodic, swift cleaning

2. **Reduced speed:** These inefficiencies stem from the variance between the speed limit and the actual operating speed of the equipment. Muchiri and Pintelon [11] discovered that utilizing non-standard pallets increased processing times for the same quantity of bottles, resulting in speed losses.

According to Trattner, A., Hvam, L., and Haug, A. in their post on December 16, 2019, slow-speed issues can be categorized into three groups [28]:

- Technology factors:

  - Reliability of technology (equipment wear, machine reliability, inadequate maintenance, production halts).
  - Technological constraints (equipment wear, insufficient equipment capability, work-in-progress queue capacity).

- Environmental constraints.

- Human factors:

  - Operator incompetence (attributable to insufficient training).
  - Measurement inaccuracies.
  - Strategic planning concerns (setting overly ambitious cycle times, inadequate targets, capacity utilization challenges, production scheduling).

Additionally, product-related factors contribute to reduced speed:

- Material availability.
- Material quality.
- Product variety.
- Product quality (quality of finished goods).

Performance = No. of products you produce / No. of products you could produce at max speed during actual working time [27]

3. Theoretical maximum speed:

Under ideal operating conditions, this represents the highest achievable speed that a machine could theoretically attain. However, in reality, it's impractical to reach this maximum due to varying conditions.

4. Nameplate capacity (NPC) or Design speed:

This refers to the maximum speed specified by the manufacturer for the device. Typically, NPC is lower than the theoretically possible maximum speed. Manufacturers may offer a more conservative estimate to ensure client satisfaction. It's conceivable that your equipment operates faster than the manufacturer's specifications, resulting in measured performance surpassing 100%.

3.2.4.3. Quality Losses and Their Impact on Output

Quality issues can result in output losses, hurting the company's profits through wasted resources or rework costs. These losses can be caused by:

Process defects or rework: These losses are caused by equipment failures. For example, if palletizers and unpackers get tangled, they can damage pallets.

Yield loss: Output decreases from the time the machine is turned on until it stabilizes. For example, a yield loss was recorded during the morning shift due to problems with the filler valves caused by the previous night shift.

Quality = Good products / All products [27]

3.2.5. OEE Measurement Tool and Integrated Performance Perspectives

3.2.5.1. Evolution of OEE

While Nakajima (1988) initially introduced the concept of OEE, subsequent definitions by various scholars have evolved over time, establishing it as a pivotal performance metric today. Jonsson and Lesshammar [2] proposed OEE as a method to identify losses stemming from production issues, whether they are persistent or sporadic. Fleischer [4] emphasizes that maintaining a competitive edge in any manufacturing sector hinges on the availability and productivity of its facilities.

Huang [5] asserts that OEE serves as a standard quantitative tool for evaluating productivity within specific equipment. Jeong and Phillips [29], however, argue that certain causes of OEE losses, such as preventative maintenance, holidays, and off-shifts, were initially disregarded in Nakajima's (1988) capital-intensive sector characterization.

Due to the inadequacies of OEE in industrial systems, modifications and expansions of its scope have been necessary. New formulations have emerged as a result of advancements in both theory and practice. Some modifications, such as Performance Efficiency Effectiveness (PEE) and Total Effective Equipment Performance (TEEP), focus on the efficiency of individual equipment pieces. At the same time, broader concepts like Overall Throughput Effectiveness, Overall Plant Effectiveness, and Overall Assembly Effectiveness build on OEE principles to evaluate the efficiency of entire production lines.

3.2.5.2. Total Effective Equipment Performance (TEEP)

Ivancic [30] introduced the concept of "Total Effective Equipment Performance" (1988), closely related to Nakajima's OEE. The key difference lies in the inclusion of scheduled downtime within the entire planned time span, rather than treating it as a separate entity. This distinction is crucial as maintenance contributes to the overall performance of the facility by minimizing unexpected downtime, also known as technical downtime.

Pintelon [11] elucidates the relationship between downtime and various breakdowns over a specified period, such as mean time between failures and mean time to repair. TEEP encompasses both scheduled and unexpected downtime, allowing for a comprehensive analysis of equipment performance. The results of a thorough downtime investigation can influence the mean time between failures (MTBF) or mean time to repair (MTTR) of equipment.

TEEP losses are integrated into the OEE model, which accounts for speed and quality losses. It is calculated by dividing available operating hours (AOH) by valuable operating time (VOT), also known as calendar time [20].

TEEP = Valuable operating time / Calendar time = OEE * Loading time / Calendar time

TEEP, akin to OEE, serves as a metric to measure machine performance and is applicable in production facilities where the entire production process is viewed as a single unit.

OEE and TEEP are closely interlinked metrics, typically utilized for on-site equipment assessment. Optimizing TEEP value through data analysis is essential before considering investments in increased capacity.

Production Equipment Efficiency (PEE), proposed by Raouf [20], focuses on weighted items, a key distinction from OEE. OEE evaluates availability, performance, and quality independently, whereas PEE assesses overall equipment efficiency, productivity, and asset effectiveness on a broader scale within the plant.

Various formulations of Overall Production Efficiency (OPE) and Overall Asset Effectiveness (OAE) have been employed in the industry over the years. Their methodologies have been tailored to meet the specific requirements of different sectors.

3.2.5.3. Underlying metrics of OEE

Availability, quality, and performance are critical components of OEE, with each having a distinct role in determining total equipment effectiveness. OEE assists in identifying six major types of machine losses by analysing these variables.

Simply put, OEE can be calculated using the following formula:

OEE = Valuable Operating Time / Loading Time [33]

- **Valuable Operating Time** is the total duration when the equipment is actively used.
- **Loading Time** is the scheduled operational period for the equipment, whether over a day, a week, a month, or a year.

Planning factor (Pf)

When assessing the availability of a product, it's essential to consider its loading time as an additional factor. A component of the TEEP statistic, the planning factor indicates the portion of the calendar year allocated for operational activities. This duration, after subtracting planned downtime [8], encompasses various facets, including:

- Insufficient staffing due to work shifts and breaks.
- Scheduled maintenance activities.
- Operator training sessions.
- Equipment trials and process enhancement endeavors.
- Routine machine cleaning and operator maintenance.
- Waiting time attributed to the completion of current orders.
- Staff shortages.
- Holidays.
- Line overhauls.
- Production modifications.

- Inspection tasks.
- Engineering operations.
- Security drills.
- Issues with external or internal materials.
- Personal time allocations.

While scheduled halts result in time loss, equipment efficiency remains unaffected by the planning factor. However, the planning factor's value typically diminishes with an increase in both planned and unforeseen losses:

Planning factor = (Planned time – Scheduled related stops)/Planned time [33]

Additionally, the total OEE can be computed as follows:

Total OEE = OEE x Planning factor [33]

Availability factor (A)

The availability factor (A) in Overall Equipment Effectiveness (OEE) measures the proportion of time a machine is operational compared to the total time it could have been operational. Factors such as unplanned downtime, setup, and changeovers are considered when calculating OEE's availability, which involves adjusting the actual output time to match the intended operating time and accounting for manufacturing time lost due to previously unrecognized stoppages.

Key Considerations

1. **Excluding Scheduled Preventive Maintenance:** Scheduled preventive maintenance is typically excluded from availability calculations because these activities can be extended or involve excessive process setup times (Dal, [8]). However, even without including scheduled preventive maintenance, poor OEE values may still be observed. This highlights the need for adopting Total Productive Maintenance (TPM) to minimize planned maintenance operations and improve overall equipment effectiveness.
2. **Activities Affecting Availability:** Several activities can impact the availability factor, leading to reduced operational time. These include:
   - **Set-up and Changeover Times:** The time required to set up machines and changeover processes between different production runs.
   - **Minor Stoppages:** Small interruptions in the production process, which can accumulate and affect overall availability.
   - **Unplanned Maintenance:** Unforeseen machine breakdowns and repairs that cause unexpected downtime.

The availability factor is calculated using the following formula [33]:

Availability = (Scheduled Production Time – Unplanned Downtime) / Scheduled Production Time

Performance factor (P)

The performance factor (P) combines the net operating rate (NOR) and the operating speed rate to assess performance within the overall energy efficiency equation. Nakajima's (1988) output measurement underscores deviations in actual output time from the intended cycle timings, as illustrated by De Groote [31].

Reasons for Utilizing Performance Metrics

Organizations employ performance metrics for several key reasons [32]:

1. **Enhancing Constructive Criticism Management:** Performance metrics facilitate the management of constructive criticism across systems. By providing clear and measurable data, these metrics help identify areas needing improvement and foster a culture of continuous enhancement.
2. **Establishing Roles and Responsibilities:** Clearly defined roles and responsibilities are crucial for fostering accountability. Performance metrics help ensure that individuals are held responsible for specific outcomes or issues, leading to greater ownership and clarity in organizational functions.
3. **Communicating Company Strategy:** Performance indicators are critical for adequately communicating corporate strategy. Companies ensure that all employees understand and work towards the same goals by aligning measurements with strategic objectives.
4. **Understanding Business Functions:** Effective information measurement requires a deep understanding of business functions. Performance metrics provide insight into the production process, allowing organizations to understand and manage their operations better.
5. **Determining Process Capacity:** Understanding a process's capacity is crucial for effective management. Performance metrics help organizations determine the limits of their processes, ensuring that they operate within optimal parameters.

Net Operating Rate (NOR)

The net operating rate (NOR) gauges the stability of the processing speed achieved over a given period. For instance, during an 8-hour production shift, NOR helps determine whether the actual pace exceeds or falls short of the design standard speed [8]. This metric allows for the assessment of losses resulting from both reported and unrecorded interruptions, such as minor flaws and adjustments. A speed loss of 20% translates to a performance of 80%.

The **performance rate (%)** is calculated as [33]:

Performance rate (%) = (Operating speed rate * Net operating rate) * 100

Where:

Operating speed rate = Theoretical cycle time / Actual cycle time

Net operating rate = (Actual cycle time * Number produced)/ Operating time

The practical application of NOR involves continuously monitoring and analyzing production speeds and interruptions. For example, if a production line is designed to operate at a certain speed but frequently experiences slowdowns due to minor faults or required adjustments, the NOR metric will highlight these inefficiencies. By addressing these interruptions, organizations can improve their overall performance and ensure that production processes operate closer to their theoretical maximum efficiency.

Moreover, understanding and utilizing performance metrics like NOR and the operating speed rate allows organizations to make data-driven decisions. These metrics provide a clear picture of where improvements are needed and help prioritize actions that will have the most significant impact on performance.

Quality factor (Q)

When assessing Overall Equipment Effectiveness (OEE), the quality rate is the final metric to consider. This metric reflects the proportion of non-defective items in the total production output. It provides insight into the effectiveness of the production process in terms of producing quality products. Quality issues in manufacturing are often caused by machine failures or production line malfunctions, resulting in defects and scrap.

The quality rate is calculated as [33]:

Quality rate = (Total quantity of produced product – Number Scrapped product)/ Total quantity of produced product

3.5.6. OEE formulation and ways to improve OEE

3.5.6.1. OEE Formulation

The efficacy of machinery, as defined by Nakajima (1988), can be quantified as a percentage based on three key factors. The formula for calculating OEE is as follows [33]:

$$\textbf{OEE} = A \times P \times Q \times 100\%$$

Where:

- **A = Availability**
- **P = Performance**
- **Q = Quality**

It is generally recommended that OEE achieves a world-class value of 85.0%, comprising:

- Availability: 90.0%
- Performance: 95.0%
- Quality: 99.9%

The overall equipment efficacy, expressed in terms of scheduled working hours, is defined as [33]:

$$\textbf{Planning factor OEE} =$$

$$\textbf{Planning factor} \times \textbf{Availability rate} \times \textbf{Performance rate} \times \textbf{Quality } \textit{rate}$$

3.5.6.2. Ways to Improve OEE

Improving Overall Equipment Effectiveness (OEE) involves employing a variety of methodologies under the broad umbrella of process improvement techniques, such as Six Sigma, the Theory of Constraints, and Lean Manufacturing. These methodologies have significantly contributed to production enhancement and have culminated in the comprehensive process known as Total Productive Maintenance (TPM) [33].

While these methods are robust and effective, they can also be complex and daunting to implement. A common question is whether it is possible to begin improvement efforts while simultaneously developing a more comprehensive program. The answer is yes.

Introducing IDA: Information, Decision, Action

To complement existing methodologies, a fourth approach called IDA (Information, Decision, Action) can be introduced. IDA emphasizes three critical factors:

1. **Information:** The foundation of IDA is built on robust and relevant information. Effective decision-making relies on data that is accurate, pertinent, and easily comprehensible. It is essential to gather comprehensive data from various points in the production process to understand where improvements are needed.
2. **Decision:** This phase involves analyzing the data and making informed choices based on the insights gained. Decisions act as the bridge between information and action,

determining what changes will be implemented, the timeframe for these changes, and who will be responsible for executing them.

3. **Action:** This is where theoretical possibilities translate into tangible progress. The decisions made in the previous phase are implemented, resulting in real outcomes. Effective action requires the coordination of resources and a focus on the weakest links in the production process to ensure swift improvements.

Implementing IDA in the Production Process

Information

Accurate and comprehensive data collection is crucial. Identify where data is being collected within the production process. Regardless of the specific production stage, whether it's bottling or packaging, the throughput will always be constrained by the slowest step or piece of equipment, known as the bottleneck. Identifying this bottleneck is essential as its performance will dictate the overall efficiency of the manufacturing process.

Decision

Analyze the collected data to determine the weakest phase in the production process. Key decisions include what changes need to be implemented, the timeline for these changes, and who will be responsible for them. Decisions should focus on the areas with the most significant losses to achieve the greatest impact.

- **Prioritize actions based on potential impact:** Focus on the areas where the most significant losses occur.
- **Ensure team readiness:** Make sure the team is prepared to act on their suggestions.
- **Minimize reliance on external resources:** Use internal resources to implement changes whenever possible.

- **Implement actions promptly:** Swift implementation is crucial for tangible improvements.

Action

Taking action is the critical phase where plans and decisions are translated into real-world achievements. To ensure successful implementation:

- **Educate and inform the team:** Provide necessary training and information to the team to prepare them for the changes.
- **Break down the improvement process:** Divide the process into manageable steps to make it more achievable.
- **Coordinate with the scheduling team:** Work with the team responsible for production scheduling to align the improvements with the production timeline.
- **Procure necessary supplies:** Ensure that all required supplies or replacement parts are available before starting the improvements.
- **Engage in active project management:** Monitor the progress of the improvement activities to ensure they stay on track.

By following the IDA methodology and focusing on the weakest links in the production process, organizations can significantly improve their OEE. This structured approach ensures that data-driven decisions lead to effective actions, ultimately enhancing the overall efficiency and productivity of the manufacturing environment.

3.5.6.3. Benefits of OEE

When implemented effectively, an OEE system can yield immediate advantages for industrial enterprises. Some of these benefits are elucidated below:

Reduced Downtime Costs

Critical machine failures halt downstream processes, potentially impacting cash flow and revenue. For instance, an hour of downtime for a major process equipment in semiconductor manufacturing could cost the industry $100,000 (based on data from 2000). A mere 1% reduction in downtime for the top 50 vital equipment pieces could generate income opportunities and expense savings exceeding $100,000,000 annually.

Reduced Repair Costs

OEE enables predictive maintenance, leading to significant reductions in repair expenses. Over time, the maintenance team can discern patterns in downtime data, anticipating potential breakdowns. Computerized maintenance management systems facilitate planned maintenance activities.

Increased Labor Efficiency

Amid the current economic climate, many industrial firms have downsized their workforces. Consequently, companies are seeking ways to enhance the efficiency of existing personnel. OEE systems prove beneficial by not only recording downtime reasons but also productivity metrics for operators. Armed with this data, management can make informed decisions regarding resource allocation based on employee productivity. By leveraging an OEE system, managers can identify additional capacity within current staff rather than recruiting new employees when business conditions improve.

Reduced Quality Costs

OEE encompasses the Rate of Quality, which pertains to the ratio of total manufactured components to high-quality parts. The system records various data including total parts produced, scrap quantity and causes, and defective component counts. By capturing quality data at the machine or line level, production managers gain insights into underlying causes, mitigating additional costs associated with rework and scrap. Improved quality throughout the manufacturing stages leads to decreased warranty costs. Studies have shown median values of 97% first-pass yields, 2% scrap and rework, and 1% warranty costs.

Increased Personnel Productivity

OEE systems facilitate digitalized shop floors, reducing the administrative burden on operators and supervisors. By automatically collecting and reporting downtime and efficiency data, the system saves time, allowing employees to focus on core responsibilities. With OEE, stakeholders from the factory floor to the boardroom are better informed, more frequently and more seamlessly.

Increased Production Capability

By minimizing machine downtime, enhancing operator productivity, and reducing faults, OEE enables increased production levels with the same resources.

4. CASE OF "ENTER SOLAR GREEN ENERGY"

4.1. Data collection

In the realm of data collection, it entails recording the values of one or more variables, with determinations made regarding what data must be recorded, how, and when. Depending on the circumstances, data collection may involve manual or automated methods. Ljungberg and Larsson [21] suggest that automated data collection methods are likely to be advantageous in the long term.

OEE calculation hinges on the manner in which data is collected. Both manual and automated data collection methods can be utilized for OEE calculations, necessitating accurate entry of variables from the production system [Ericsson, 35]. Manual data collection is common in low-tech industries, where personnel fill out logbooks detailing failures and performance losses. Conversely, high-tech industries employ automated OEE calculation systems that record start times and shutdown durations automatically, while prompting operators to provide accurate downtime reason information. Operators can access lists of potential downtime reasons, plan runtime, and generate automatic OEE estimates for specific periods using automated techniques. If data entry is integrated into the system, not only can OEE results be generated, but a range of reports and process performance visualizations can also be obtained. However, an excess of information in the system may require operators to search for each outage reason individually, resulting in inefficiencies. Many businesses face challenges due to operators and supervisors being hesitant to gather data. Ljungberg [21] argues that operators must be convinced that some disruptions do not significantly impact efficiency, a notion supported by subsequent measurements. Automated data collection is costly, complex, and time-consuming. Conversely, manual data gathering can be meticulous, allowing for thorough investigation of losses. As a performance metric, OEE necessitates a blend of both human and automated data gathering methods, along with training OEE personnel on various aspects impacting OEE. This serves two primary purposes: enhancing operator proficiency and empowering operators to play a more active role in identifying potential performance loss issues and providing accurate information to the system. OEE data was collected over a three-month period from various types of equipment across diverse sectors, following Ljungberg's recommendation [21], with machine stops recorded using a computer and assistance from operators.

4.2. Setup time

Taiichi Ohno, the former president of Toyota in the 1950s, expressed frustration over Toyota's practice of producing vehicles for stock, resulting in consumers waiting unnecessarily for their automobiles. This inefficiency stemmed from the company's manufacturing of components and finished products in large batches. By implementing lean manufacturing techniques, Van Goubergen and Van Landeghem [34] contend that reducing machine setup time impacts production costs, particularly for smaller series orders.

During setup time, machines remain idle as preparations are made for the next manufacturing task to commence. During this time, activities may include removing and cleaning previous tools, loading new tools and settings, checking and testing equipment, and significantly reducing equipment downtime. Although setup time is commonly regarded as a scheduled task required for operations, it adds to downtime losses that can be reduced and is thus critical in determining overall efficiency (OEE). Setup durations can range from long to quick, depending on the machine and unique requirements.

Several reasons may contribute to machine downtime, including program failure, tool changes, waiting for containers or missing tools, machine failures, cleaning and maintenance, material loading, setup procedures, and inspections.

According to Van Goubergen and Van Landeghem [34], reducing setup times allows customers to purchase more items in smaller series, thereby increasing throughput by reducing installation periods of bottleneck units, ultimately enhancing company revenue. Suzaki (1987) emphasizes the importance of industrial operations being flexible enough to respond swiftly to market changes, with businesses striving to offer a wider range of products to meet customer demands. Standardized components enable the operation of multiple items on a machine simultaneously, reducing setup time and facilitating knowledge transfer across products (Pratsini, [35]). Techniques such as Single Minute Exchange of Dies, a set of standard approaches introduced by Shingo [36], further reduce setup time and enhance operational efficiency.

4.3. Cycle time

Continuous manufacturing cycle time denotes the duration required to produce a product. As stated by Ljungberg [21], the operational speed per hour is established based on the time taken to accomplish each task. Cycle periods are further categorized into long and short durations; however, if items are rejected after production, it is usually classified as a long cycle period and referred to as losses. Cycles are influenced by factors such as design speed, initial ideal conditions, and product modifications (Nakajima, [6]).

4.4. Single Minute Exchange of Dies (SMED)

Shigeo Shingo introduced the concept of Single Minute Exchange of Dies (SMED) in the 1950s, driven by the need for flexibility in Japan's manufacturing landscape, which increasingly demanded smaller production batch sizes to meet consumer demands. SMED serves as a method to minimize manufacturing waste by enabling rapid and seamless transitions to subsequent products (Shingo, [36]). The term "single minute" denotes the time needed for all changeovers and setup processes, which is typically less than 10 minutes.

4.4.1. The benefit of setup reduction.

The advantages of implementing Single Minute Exchange of Dies (SMED):

- Reducing waste and excess inventory reduces production costs.
- Faster changeovers enhance product quality by reducing errors that can occur during setup.
- Manufacturers can respond quickly to changing production needs, resulting in more flexibility.
- Minimising downtime through timely adjustments leads to improved machine performance and reduced idle time.
- SMED prioritises continuous improvement to improve setup processes and increase operational efficiency.
- Shorter setup times allow for more manageable batch sizes, boosting efficiency and reducing storage needs.
- Standardised and efficient setup procedures ensure constant manufacturing quality.

The SMED process involves two main steps:

1. Identifying and Separating Internal and External Setups:

- External setups are performed while the system is still operating, while internal setups are carried out when the system is shut down.
- External setup tasks are completed before the machine finishes processing a product, ensuring readiness for the next setup.

2. Converting Internal Setups to External Setups:

- Converting indoor installations to outdoor installations simplifies both processes, increasing efficiency.
- Workers can complete outdoor installation tasks, such as cleaning and material handling, during the indoor installation period.

Additional steps to creating a SMED include:

1. Organizing the workspace and using quick-connect fittings and fasteners can reduce the amount of indoor installation work.

2. Standardization of components and materials can save setup time. Regular setup activities, as well as continuing enhancement efforts, help to reduce setup time further.

4.5. Why's analysis

Why's analysis is a method used to explore the fundamental cause-and-effect relationships behind a specific issue. It is crucial, as highlighted by Slack [37], to identify the underlying cause of a problem or flaw. This approach does not solve problems directly but rather serves as a means to uncover the origins of an issue. Identifying the problem's root cause is essential for effective problem-solving.

This strategy is particularly useful when dealing with minor difficulties, recurring problems, or issues stemming from operator errors or social interactions, especially for individuals with limited expertise or experience. Why's analysis is a straightforward, effective, thorough, adaptable, engaging, and cost-effective root cause analysis tool.

Consider the following example:

Statement: The machine keeps failing.

- **Why did the machine fail?** The circuit board burned out.
- **Why did the circuit board burn out?** It overheated.
- **Why did it overheat?** There wasn't enough airflow.
- **Why was there insufficient airflow?** The filter was clogged and hadn’t been replaced.
- **Why wasn’t the filter replaced?** Regular maintenance was neglected, and the employee wasn’t aware it needed changing.

4.5.1. Analysis

Working at ENTER SOLAR GREEN ENERGY entails providing both quantitative and qualitative information, including interview material which may be challenging to measure. While quantitative data offers numerical insights, qualitative data provides a deeper understanding of the underlying statistical results.

During this phase of analysis, continuous exploration of challenges and opportunities is essential. Difficulty in determining suitable analyses or formulating actionable judgments and strategies may raise concerns about the accuracy and usability of assessments. Given the necessity to adhere to tight project deadlines, meticulous planning was imperative. To facilitate project management and ensure clarity of timelines, Microsoft Project was utilized to create a Gantt chart, depicting the entire project timeline, including meetings with supervisors.

4.5.2. Validity and Reliability

Effectiveness and relevance alone do not suffice for a research study to be considered robust; its validity and reliability must also be assessed. The structure and design of the questionnaire are pivotal in obtaining reliable and accurate information, as they mitigate the risk of subjective question construction [15].

Throughout the investigation, meticulous procedures were implemented at every stage, from data collection and analysis to hypothesis formation, to uphold the reliability and validity of the findings. Utilizing a questionnaire-based approach was instrumental in ensuring the accuracy and validity of the data. Additionally, employing raw data analysis, descriptive statistics, and regression analysis enhanced the accessibility and comprehensiveness of the research findings.

	Reliability	Validity
What does it tell?	The degree to which outcomes can be replicated under similar conditions determines their repeatability.	To what extent can they accurately measure their intended target?
How is it assessed?	Ensuring that outcomes maintain consistency over time, across different observers, and within the test itself is crucial.	This is determined by assessing the alignment of findings with existing theories and alternative methods used to evaluate the same subject.
How do they relate?	Although results may be consistent and repeatable, it doesn't necessarily imply their accuracy, indicating that reliability does not always equate to validity.	Typically, a valid measurement also demonstrates reliability, with reproducibility serving as an indication that the test provides accurate results. [16]

Validity in this context necessitates standardized practices across the entire sector, fostering effective communication among personnel. It also relies on worker engagement and responsiveness to deviations in manufacturing processes, as highlighted by Freivalds [18]. The validity of efficiency improvements and the mitigation of errors by new workers are contingent upon a consistent working environment. Establishing validity can be achieved through various means.

4.5.2.1. Types of Validation in Research

- Face validity: This intuitive approach involves experts evaluating whether a measure appears to be grounded in the hypothesized concept.
- Concurrent validity: Researchers use this type of validity by comparing a measure to a criterion known to vary across examples and relevant to the problem under investigation.
- Predictive validity: The validity of a novel measure, such as job satisfaction, can be assessed by its ability to predict future outcomes, such as absence levels.
- Construct validity: This approach suggests formulating hypotheses that align with the underlying theoretical framework.
- **Convergent Validity:** Assessing the accuracy of a measurement by comparing it with other measurements of the same concept that were gathered using different approaches [19].

Various approaches to evaluating validity exist, but the core principles remain consistent. This research utilized these methods to validate its findings. Discussions during meetings frequently addressed machine idleness, and engineers assisted operators in verifying cycle times and changeover times across all machines.

According to Saunders [17], there are limitations to data collection, including time constraints, potential biases, and cost considerations. However, industry approval was largely obtained for data acquisition.

The reliability of a solution's ability to measure something determines its trustworthiness. Three key aspects to consider when assessing measurement reliability include dependability, downtime, and mean time between failures (MTBF) [12]. Improving MTBF can enhance machine availability and efficacy by reducing downtime and enhancing repair quality.

4.5.2.2. Types of Reliability in Research

- Internal reliability: This refers to the consistency of a certain indicator across different measures or indicators within a survey. It assesses whether the results obtained are coherent and correlate with each other.
- Stability: Stability reliability measures the consistency of results over time. If a measure demonstrates high stability, it means that the results obtained from the same sample of respondents will remain consistent when the measure is administered at different points in time. Minimal variation in results should be observed when a test is administered, and then re-administered to the same sample.
- Inter-observer consistency: This form of reliability assesses the degree of agreement among different observers when performing tasks such as recording observations or categorizing data. In situations where multiple observers are involved, discrepancies in their interpretations of data may lead to contradictory findings. This may occur when classifying media objects in a literature review or making judgments about participant behavior in observational research.

4.5.3. Efficiency and Effectiveness

The distinction between efficiency and effectiveness is often misunderstood in the context of measuring productivity. While traditional terminology referred to "overall equipment efficiency" (OEE), current terminology uses "overall equipment effectiveness" (OEE). Efficiency represents the ratio of actual input to a reference value, whereas effectiveness represents the ratio of actual output to a reference result [20].

Equipment efficiency pertains to the ability of equipment to operate at a low cost, but contemporary production and business objectives have evolved beyond solely focusing on equipment efficiency. The concept of Equipment Effectiveness (E.E.) defines an industry's ability to consistently deliver the goods and services it requires [20]. In essence, effectiveness involves doing the right things, while efficiency involves doing the right things the right way consistently.

Productivity measurement involves assessing the number of finished items produced by an individual compared to the hours spent at work. In modern "lean" workplaces, emphasis on efficiency rather than OEE may better serve productivity goals.

4.6. Research Approach

Before commencing a research project, selecting an appropriate data collection strategy is crucial. The majority of scientific research utilizes quantitative and qualitative data collection approaches [13].

4.6.1. Quantitative Method:

This method highlights numerical data and statistical analysis. It involves collecting samples from each individual and comparing them using several critical variables. Relying on observed data provides an objective perspective and helps understand research and theoretical concepts. Researchers can evaluate phenomena by collecting numerical data and analysing them using mathematically based methods such as statistics [12].

This study used a quantitative approach focusing on overall equipment effectiveness, which is consistent with Seiichi's TPM philosophy, which uses OEE as a quantitative metric to evaluate the efficiency of each production unit in a plant.

4.6.2. Qualitative method

According to Gummeson [14], qualitative research extensively utilizes non-numerical data to delve into the intricacies of the research topic, aiming for a comprehensive understanding of its characteristics. This approach seeks to uncover the underlying causes and motivations behind a given scenario. It allows for a nuanced exploration of various factors within a sample group, offering insights into how to effectively manage or address them. Darmer and Freytag highlight the high level of flexibility and adaptability inherent in qualitative research, whether conducted independently or alongside quantitative research. Distinguishing between quantitative and qualitative data is paramount.

4.7. Case study

4.7.1. About the company

Enter Solar is a pioneering industrial company in Central Asia, leading the region in innovative solar panel manufacturing technologies. Equipped with cutting-edge equipment, including a fully automated production line sourced from industry leader Ecoprogetti in Italy, Enter Solar is at the forefront of the renewable energy revolution.

Enter Solar's 200 MW annual production capacity enables it to produce a staggering 367,540 units of PV modules annually. These modules, with ratings ranging from 520 to 540 V, describe the solar panel technology model. Enter Solar specializes in monocrystalline PV modules with bifacial PERC M10 cells, and also offers monocrystalline PV modules based on M6 cells to meet different market needs.

Operating in this area might be difficult because consumers are increasingly placing little orders and expect them to arrive fast. Any delays or damage that occur throughout the manufacturing process may have a detrimental influence on the customer experience. Many international standards must be followed, and profit margins are tight and complex.

Enter Solar provides various advantages because of its cutting-edge manufacturing processes and commitment to innovation in the solar energy sector:

- Cutting-edge Technology: Enter Solar utilizes state-of-the-art equipment and fully automated production lines sourced from industry leaders like Ecoprogetti in Italy. This ensures high-quality manufacturing processes and superior product performance.
- High Production Capacity: With a production capacity of 200 MW per year, Enter Solar can meet the growing demand for solar panels in Central Asia and beyond. This

high capacity allows the company to scale production to meet market needs effectively.

- A wide range of solar solutions. Enter Solar specialises in high-efficiency monocrystalline PV modules with sophisticated two-sided PERC M10 cells that deliver superior performance. The company also offers monocrystalline PV modules using M6 cells, giving customers various solutions to fit their demands and project specifications.
- Commitment to innovation and sustainability. Enter Solar is dedicated to pushing the boundaries of solar technology while advocating sustainability.
- Regional Leadership: As the first and only enterprise of its kind in Central Asia, Enter Solar establishes itself as a leader in the region's renewable energy industry. Its presence signifies progress towards a cleaner and more sustainable energy future for Central Asia.

4.7.2. Existing problems

Common problems in solar panel manufacturing:

1. Downtime due to equipment failures: Equipment breakdowns can lead to significant downtime in the manufacturing process, reducing overall productivity.
2. Quality issues such as defects and rework: Imperfections in solar panels can reduce their efficiency and lifespan, leading to customer dissatisfaction and warranty claims.
3. Inefficient cycle times: Lengthy production cycles can limit the manufacturing capacity and slow down the delivery of solar panels to customers.
4. Suboptimal resource utilization: Poor utilization of raw materials, energy, and labor can increase manufacturing costs and environmental impact.

5. Lack of predictive maintenance: Reactive maintenance practices can result in unexpected equipment failures and unscheduled downtime.
6. Challenges in production planning: Inaccurate forecasting and capacity constraints can lead to underutilization or overutilization of manufacturing resources.
7. Operator training and engagement: Insufficient training and motivation among operators can lead to inefficiencies and errors in the manufacturing process.

4.7.3. Data Analysis

This study explored the process of data collection and analysis in solar panel manufacturing. Over 64 working days, with two shifts per day, researchers gathered detailed measurements, observations, and interviews to gain insights into production efficiency and quality.

A strong focus was placed on quantitative methods, using internal databases to track numerical data on manufacturing operations. On average, about 2,500 solar panels were processed daily. In addition, qualitative techniques were applied, including random sampling to evaluate repair times and assess technical quality.

TPM emerged as a focal point, aiming to optimize equipment maintenance for enhanced productivity within the manufacturing plant. However, it was observed that TPM implementation slightly lagged behind industry standards, particularly in addressing electric and mechanical concerns. Breakdowns necessitated the intervention of specialized engineers, leading to operational halts and a decline in performance metrics.

Additional investigation indicated possible reasons behind malfunctioning equipment like overheating and interconnections among system blocks. Workforce shortages at times also compounded this need, as these breakdowns had a dramatic effect on OEE. Even under these conditions, tight quality controls ensured only minimal quality losses, all of which was beneficial to OEE.

TEEP (Total Effective Equipment Performance) became a key metric and is the result of OEE times Utilization. For solar panel production the percentage of time machines are actually used effectively is called utilization and this uncoverd a huge untapped opportunity for productivity in the solar panel production process.

Calculation:

- $All\ Time\ =\ Total\ number\ of\ days\ \times\ 24\ hours/day$
- $Planned\ Production\ Time\ =\ Total\ working\ days\ \times\ Hours\ per\ shift\ \times\ Number\ of\ shifts$
- $Utilization\ =\ \frac{Planned\ Production\ Time}{All\ Time}$

Breakdown of downtime:

- Change-over time
- Maintenance (electric and mechanical)
- System pause time
- Other planned stops
- Workforce absence
- Micro stoppages
- Quality checks

Understanding and addressing these challenges through data-driven analysis are critical steps toward optimizing efficiency and productivity in solar panel manufacturing.

Where:

- $All\,Time \;=\; 92\,days \;\times\; 24\,hours/day \;=\; 2208\,hours$
- $Planned\,Production\,Time \;=\; 64\,working\,days \;\times\; 2\,shifts \;\times\; 8\,hours/shift$
- $Utilization \;=\; \frac{1024}{2208} \;=\; 46.38\,\%$

Now, let's calculate TEEP: $TEEP \;=\; OEE \;\times\; Utilization$

Given:

- Utilization ≈ 46.38%

We need to calculate OEE. OEE is calculated using three factors: Availability, Performance, and Quality.

$$Availability \;=\; \frac{Total\ scheduled\ production\ time - Total\ downtime}{Total\ scheduled\ production\ time}$$

- Total scheduled production time = 1024 hours

$$Total\ downtime \;= Change\ over\ time \;+\; Electric\ maintenance \;+\; Mechanical\ maintenance \;+\; Pause\ time \;+\; Other\ planned\ stops \;+\; Absence\ of\ personnel \;+\; Micro\ stoppages \;+\; Quality\ check$$

- Total downtime = 201 hours + 3.5 hours + 12.8 hours + 48 hours + 30.5 hours + 80 hours + 37 hours + 58.5 hours = 471.3 hours
- Availability = (1024 - 471.3) / 1024 ≈ 54.00%

$$Performance \;=\; \frac{Total\ operation\ time\ /\ Total\ scheduled\ production\ time}{Availability}$$

- Performance = (552.7 / 1024) / 0.54 ≈ 0.972

- Quality = 1 (since no significant quality losses were mentioned)

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

- OEE = 0.54 * 0.972 * 1 ≈ 0.525

Now, calculate TEEP:

$$TEEP = OEE \times Utilization$$

- TEEP = 0.525 * 46.38% ≈ 24.33%

So, the TEEP for the solar panel manufacturing process is approximately 24.33%. This indicates the percentage of All Time that is truly productive considering the Overall Equipment Effectiveness and Utilization.

5. CONCLUSIONS

This study has undertaken a thorough examination of Enter Solar's equipment efficiency, meticulously identifying and quantifying all equipment losses. Overall Equipment Effectiveness (OEE) has provided invaluable insights into the efficiency of various processes within the plant.

Enhancing productivity and achieving a higher return on investment (ROI) are pivotal in bolstering a manufacturing industry's competitiveness through OEE. World-class performance, denoted by an OEE rating of 85%, signifies availability, performance, and quality rates at or above 99.9%. The discrepancy between ideal and actual states, influenced by possible losses, significantly impacts this metric. Williamson [61] contends that there is no distinct world-class value, an assertion echoed in this study's findings. Another major challenge that negatively impacts OEE is setup and changeover times, significantly when changing the product mix. Only the average quality factor can maintain that optimal value out of all the OEE metrics above. Availability usually lags in business primarily due to substantial losses or exceptional interruptions.

The projected world-class value for quality in OEE also shows little quality loss, but availability is the most significant loss. There's a pressing need for heightened awareness and a training program across the industry to underscore the value of knowledge in decision-making and continuous improvement initiatives. The lack of mention regarding stoppage reasons underscores the need for further research.

Enter Solar's average OEE falls below par, suggesting a misalignment with OEE principles and a failure to implement essential practices. Probable reasons include overestimation of equipment efficiency, lack of operator training, technological complexity, procrastination, fear of performance evaluation, malfunctioning systems, operator disengagement, disregard for historical data, management shifts, and a focus solely on accounting rather than progress.

Overcoming employee resistance to change requires concerted internal communication efforts and ensuring clear comprehension of the message. Sustaining long-term competitiveness mandates continuous performance improvements. Techniques like the 5 Whys or Fishbone Diagrams can be employed to unearth root causes of loss-related events. Data quality remains paramount, necessitating investments in automated monitoring systems to bolster credibility.

As industries embrace new technologies and equipment, the risk of crucial system failures rises, impacting operators' capacity due to unplanned losses. OEE offers numerous advantages, including accurate information, optimal utilization of infrastructure, data-driven decision-making, and energy efficiency and quality monitoring.

Availability-related losses predominantly drive poor OEE across industries. Addressing setup and changeover inefficiencies through Single-Minute Exchange of Die (SMED) can mitigate inventory costs and better meet customer needs.

Prior to implementing any changes, comprehensive communication and explanation to all stakeholders are essential. Educating and empowering individuals foster greater self-awareness and acceptance of change. Additionally, tailored systems must be developed to suit industry-specific processes. Qualitative research methods, such as interviews and questionnaires, can yield valuable insights from cross-functional teams.

Long-term considerations may entail preventive maintenance or vibration analysis to address unforeseen machine malfunctions. Topics for future exploration include operational and production design, cost-effectiveness assessments of equipment, machine and mechanical design, and human OEE frequency studies.

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