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Integration Project

Faculty of Science and Engineering

# SWOT Analysis: Developing the key figure Overall Equipment Effectiveness (OEE)

Group 14

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# Abstract

OEE is considered the key performance measurement for successful implementation of Total Productive Maintenance (TPM) activities, combining its three main pillars in one metric. OEE is and still becoming increasingly popular, being used as a quantitative tool essential for measuring productivity and improving their asset utilization. Despite its many benefits, like all available business metrics, the key figure OEE has received a lot of criticism both in literature and application, whilst researchers are yet to comprehensively address this issue. As such, this research will aim to address this knowledge gap via exploring the strengths, weaknesses, threats, and possible opportunities as to how to further develop or redesign this metric to overcome some of its limitations. This research's findings are valuable as it provides production managers with a better understanding of OEE, and a more comprehensive tool acting as an extension to the maturity of OEE for successful implementation and use of this performance indicator.

From the SWOT analysis, two main weaknesses of OEE were chosen to focus on: it categorizes losses in a way that merges all downtime events, inhibiting a more detailed loss classification scheme, and it does not account for changes in market demand. Consequently, two new factors, usability and customer requirement rate, were incorporated into the original OEE method to overcome its identified limitations. A three-case numerical example was used to demonstrate the benefits of the proposed OEE. It was applied and compared with the original OEE method using a one-machine model, representing a generic bottleneck process, with the parameters customer demand and planned downtime being manipulated throughout the three cases. The new OEE measurement's value can mainly be attributed to its more meticulous classifications of losses, and its recognition of customer demand fluctuations. These two additional characteristics of OEE contribute to its expansion and maturity as a TPM performance measurement system.

Keywords: *Overall Equipment Effectiveness (OEE); Performance measurement; Performance evaluation; Production equipment; Effectiveness; Manufacturing; Operations management; Total productive maintenance (TPM)*

# Contents

# 1 Introduction

The prevailing trend of corporate globalization has led companies to be pressured to seek continuous improvements in their production facilities in order to continue to survive (Ng, Chong and Goh, 2014; Mahmood et al., 2016). Consumers, as an external pressure, are becoming more focused on quality, delivery time, and cost of products (Gupta and Garg, 2012). This resulted in the expansion of the competition base for businesses in all industries (Muchiri Pintelon, 2008), and as a consequence, shorter time to market and product life cycles (Hubl and Gmainer, 2008). In order to stay competitive, companies are forced to implement a broad range of productivity improvement programs, such as developing and implementing total productive maintenance initiatives (TPM) (Muchiri and Pintelon, 2008). (Nakajima, 1989) defines TPM as *"a plant improvement methodology which enables continuous and rapid improvement of the manufacturing process through the use of employee involvement, employee empowerment, and closed-loop measurement of results."*

(Ljungberg, 1998) argues that TPM is built upon three main pillars: maximizing equipment effectiveness, autonomous maintenance by operators, and small group activities. One of the most commonly used tools of TPM is the key figure Overall Equipment Effectiveness (OEE), which is responsible for combining all three TPM targets in one metric (Ljungberg, 1998; Hubl and Gmainer, 2008). It is considered in both literature and practice as the key performance measurement for successful implementation of TPM activities (Ng et al., 2014). According to Bamber et al. (2003), Dal et al. (2000), Lijunberg (1998), De Ron and Rooda (2006), Muchiri and Pintelon (2008) and Hubl et al. (2009), OEE is and still becoming increasingly popular, used by more and more companies as a quantitative tool essential for measuring productivity; companies in various industries have adopted it to improve their asset utilization (Muchiri and Pintelon, 2008).

Mahmood et al., (2016) argue that OEE can be considered the starting point for productivity optimization of manufacturing equipment, and therefore it is a main driver towards operational excellence. It is a significant metric that mainly focuses on maximizing equipment effectiveness and reducing losses that negatively affect the production process. In practice, OEE is not only used as an operational measure, but also as a process improvement indicator within the confines of the production system or plant (Ng et al., 2014). (De Ron and Rooda, 2006) emphasize that metrics are absolutely necessary to measure production performance as it improves control, sets clear quantifiable responsibilities and objectives, enables strategic alignment of objectives, assists in understanding business processes, and helps determine process capability.

Like all available business metrics, frameworks, or strategies, the key figure OEE has received a lot of criticism both in literature and application, whilst researchers are yet to comprehensively address this issue. This research will aim to address this knowledge gap via exploring the strengths, weaknesses, threats, and possible opportunities as to how to further develop or redesign this metric to overcome some of its weaknesses or limitations. Even though this is a theory-oriented research, the practical relevance of the project is evident as it provides organizations, and their managers, with a better understanding of the OEE metric in the midst of the vast pool of literature and controversy surrounding it and a more comprehensive tool acting as an extension to the maturity of OEE for successful implementation and use of this performance indicator.

## 1.1 Problem Context

In spite of the fact that the OEE measurement is widely recognized as a proficient robust key performance indicator, it is not without criticism prompting further investigation. The first limitation of OEE, which is heavily cited in literature, can be credited to the different definitions of OEE elements and calculation methods, which hinder the efforts of identifying optimum OEE figures and benchmarking (Jonsson and Leeshammar, 1999). Also, the OEE calculation does not factor in all variables that may affect utilisation, such as planned downtime and lack of material input (Ljungberg, 1998), hence a substantial part of losses is neglected. Yalagi et al. (2016) state that the definitions and conditions of use of OEE have been up for debate in literature since it was first introduced by Nakajima (1989); the abundance of definitions and suggested uses of OEE has resulted in significant confusion for management practice, especially when attempted to be used for benchmarking or comparing machines, plants, and even companies. Many researchers advocate that OEE may be applied to any individual work center, or rolled up to department or plant levels for internal and external benchmarking and identification of the worst machine performance to dedicate TPM efforts and activities to (Dal et al., 2000; Hubl and Gmainer, 2008; Mahmood et al., 2016); on the contrary, some studies emphasize that OEE was not designed for benchmarking purposes and that it has just evolved to accommodate these levels of misuse (Yalagi et al., 2016).

Moreover, expanding the purpose of OEE from solely as performance indicator to an improvement driver is not utilized to its fullest potential due to the ambiguities of OEE's definitions and interpretations (Andersson and Belgrann, 2015). Furthermore, OEE is not a statistically valid metric, but has been used as such for the past decade or so, and it does not provide root causes regarding machine inefficiency, but just contributes in categorizing the losses or areas for improvement activities (Yalagi et al., 2016). Other limitations exist in respect to the implementation of OEE, which uncovers that the nature of the OEE metric encourages users to maximize utilization with total disregard to customer demand (Hubl et al., 2009), which has potential negative implications on logistical drivers, such as lead-time, inventory, and delivery reliability (Puvanasvaran et al., 2013; Hubl and Gmainer, 2008). (Puvanasvaran et al., 2019) argue for yet another limitation in OEE's visualization of wastes; in despite of its identification and categorization of the six big losses, it still was not able to pinpoint the exact areas of improvement effectively, which further induces the need and urgency for a modified OEE calculation or metric.

OEE provides a quantitative metric based on availability, performance, and quality elements only for assessing the performance of equipment or processes. Despite the significance of these three performance indicators, OEE neglects other important performance factors such as the efficient usage of raw materials, production system, logistics, labour, etc., parameters that may have a significant effect or contribution to the performance of the machine or process being examined (Garza-Reyes, 2015). This prompted numerous studies that have attempted to expand the scope of OEE through the inclusion of more elements of performance. An overview of a few of these efforts will be discussed in the following chapter.

## 1.2 Problem Statement

From the problem context and preliminary problem analysis, the following problem statement has been deduced:

> *The global pace of market uncertainty within the manufacturing industry has compelled companies in all sectors to seek continuous improvements in their production performance. Consequently, performance measurement systems are crucial for initiating and directing the drive for production improvement. OEE is one of the key performance indicators (KPI) of TPM activities. However, the potential of using this measure in industry as an essential optimization driver is not fully utilized as a result, for example, of OEE's lack of certain factors that may significantly affect process performance.*

## 1.3 Aim and Research Question

The research objective is to further develop the current OEE metric, by conducting a SWOT analysis to critically evaluate OEE as a performance indicator, and the proposed modified OEE metric, acting as an extension to the maturing of OEE, that mitigates some of its identified limitations. Extensive literature review, supported with mathematical modelling through numerical examples, is conducted in order to realize this goal within 3 months. As such, the subsequent research question has been formulated for steering and guiding the research:

- In what way can the original OEE metric's scope be expanded in order to better represent production performance?

## 1.4 Research Scope

As illustrated in the problem context, the problems involved with the current OEE measurement are so extensive and complex which requires this research to isolate a specific problem or set of problems to focus on in order to contribute towards a solution to the overall problem, the inefficiency of the current OEE metric. Hence, one of the objectives of this research is to assess OEE as a performance measurement system and delineate and identify certain areas that this research can address. It is important to emphasize that the OEE principle is still becoming more and more accepted in the manufacturing industry, in many sectors like in semiconductor and electronic equipment, pharmaceutical, or even the food industry. Consequently, the researcher decided to delineate the problem context to evaluate the OEE metric in the manufacturing industry in general, not specifying a certain sector, customer order decoupling point, or geographical region. This decision is validated upon reviewing acclaimed journal articles (Ljungberg, 1998; Jonsson and Lesshammar, 1999; Kwon and Lee, 2004; De Ron and Rooda, 2006; Ferko and Znidarsic, 2007; Badiger and Gandhinathan, 2008; Puvanasvaran et al., 2013; Sivaselvam and Gajendran, 2014; Binti Aminuddin et al., 2016) which evaluated and developed the OEE metric without specifying or limiting their findings to any of the aforementioned scopes or lenses.

## 1.5 Research Outline

In this subsection, the research structure is developed into a schematic and visualized framework (Figure 1) of the research steps required to achieve the research objective.

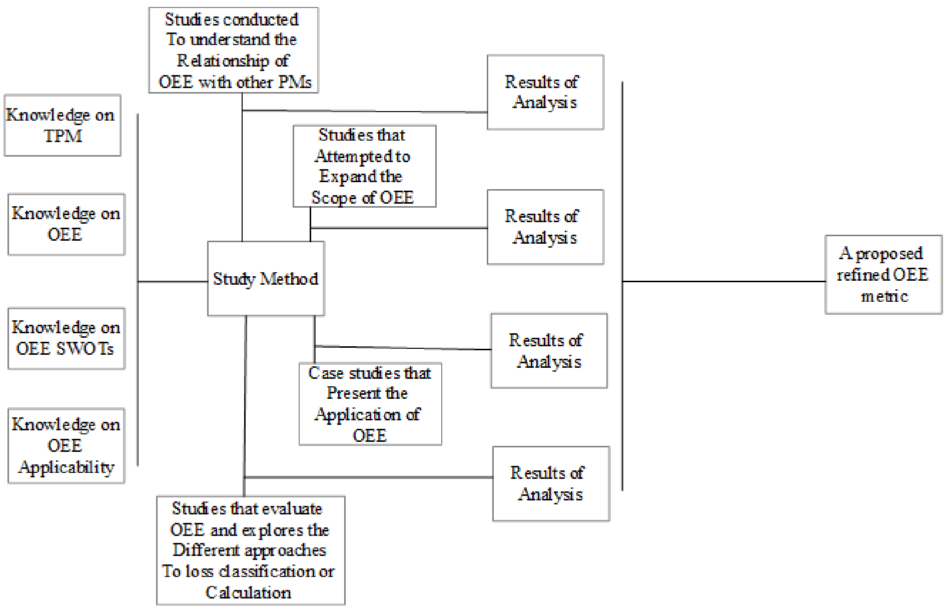



Figure 1: Research Framework

The framework is divided into four sections. The first column identifies the areas of knowledge which will be used in identifying, exploring, and assessing the research object, OEE. The second column entails evaluating the findings in the different studies, while the third column translates to a synergy and critical analysis of the results from the previous column. Lastly, the research outcome is visualized, a proposed modified refined OEE metric. As such, the research outline is as follows.

This integration project consists of seven chapters. Chapter 1 provides a brief discussion of the state of the art, the background of the problem supported with a preliminary problem analysis, research aim, scope, and paper outline. Chapter 2 presents the findings of previously conducted OEE literature that address similar issues in this body of knowledge, consisting of observing OEE's current state in literature, identifying the problems, composing a literature study, data collection and analysis of problem. The product of this literature survey facilitates the creation of the SWOT analysis that is undergone in Chapter 3, enabling further problem delineation, an increase of research focus, and finally formulating the newly proposed OEE metric in Chapter 4.

Chapter 5 and 6 inspect how the proposed refined OEE metric, which introduces three new elements to the three original OEE elements: availability, performance, and quality, assists in mitigating some of the issues identified in the SWOT analysis. Additionally, the new metric is applied to a one-machine model representing a generic production system in a manufacturing environment, using numerical examples. Moreover, Chapter 6 serves the purpose of demonstrating the results obtained from the run computations of different scenarios, emphasizing the drawbacks of the original OEE calculation method and to illustrate the advantages of the new OEE metric proposed in Chapter 4. Finally, Chapter 7 provides the concluding arguments based on the efforts exerted in this paper, discusses the research's limitations, and suggests recommendations for future research.

# 2 Literature Review

## 2.1 Methodology

For the desk research literature review strategy, a direct search method is required to locate any relevant literature and publication. A summary of the literature search method used can be found below (Table 1). The reviewed papers were selected out of an abundance of literature based on relevancy. A great number of papers incorporated into the literature review results in a reliable comprehensive study. OEE is advertised as one of the most significant performance measurement systems in a manufacturing environment for measuring productivity and as a continuous improvement driver or tool (Garza-Reyes et al., 2010; Andersson and Bellgran, 2011). This resulted in a broad range of scholarly articles being published, further contributing to the OEE body of knowledge. Table 1 classifies four types of journal articles and conference proceedings that have been conducted in the past 22 years.

| **Summary of Literature Search Method Used** | |
|---|---|
| Unit of analysis | Relevant journal articles and conference proceedings published on the critical discussion of the key figure OEE as performance measurement tool. Insights were sought regarding the purpose, benefits, weaknesses, and possible improvements of the current figure. |
| Type of analysis | Qualitative |
| Period of analysis | 1989-2020 |
| Search engines | SmartCat, Google Scholar, WorldCat, Emerald, Business Source Premier, Lexis Uni, and Research Gate |
| Keywords used in searches | Overall Equipment Effectiveness (OEE); Performance measurement; Performance evaluation; Production equipment; Effectiveness; Manufacturing; Operations management; Total productive maintenance (TPM) |
| Main journals used in this paper | International Journal of Production Research (7); Journal of Quality in Maintenance Engineering (6); International Journal of Operations and Production Management (5); International Research Journal of Engineering and Technology (2); International Journal of Quality and Reliability Management (2); International Journal of Productivity and Performance Management (2) |
| Total number of articles and conference proceedings retrieved | 50 |

Table 1: Search Method

Despite the indication that there is an abundant amount of academic studies dedicating their efforts to present the application of OEE, expand its scope of application, explore its relationship with other performance measures, this body of knowledge is still under development and revision with the purpose of seeking an optimum OEE metric. The studies presented in the second row of Table 2 have all attempted to expand the scope of OEE's application by enlarging its purpose or through the inclusion of more elements. To complement this body of knowledge, this research aims to build upon their findings and from the findings in other areas of research in order to realize the research goal.

| **Area of Research** | **Author(s)** |
|---|---|
| Studies that present the application of OEE through case studies | Ljungberg (1998); Jonsson and Leeshammar (1999); Dal et al. (2000); Bamber et al. (2003); Ferko and Znidarsic (2007); Olhager et al. (2010); Kumar et al. (2012); Ng et al. (2014); Sivaselvam and Gajendran (2014); Kumar and Soni (2014); Hedman et al. (2016); Mahmood et al. (2016); Gupta and Vardhan (2016); Binti Aminuddin et al. (2016); Sajid et al. (2018); Shakil and Parvez (2020); Cheah et al. (2020) |
| Studies that have attempted to expand the application scope of OEE by enlarging its purpose or through the inclusion of more elements of performance than just availability, performance and quality | Oechsner et al. (2003); Muchiri and Pintelon (2008); Hubl et al. (2009); Wudhikarn et al. (2010); Roessler and Abele (2013); Kumar and Soni (2014); Garza-Reyes (2015); Roessler and Abele (2015); Domingo and Aguado (2015); Yalagi et al. (2016); Che Maideen et al. (2017); Puvanasvaran et al. (2019) |
| Studies conducted to understand and explore the relationship between OEE with other performance measures or approaches | Kwon and Lee (2004); Gibbons and Burgess (2010); Garza-Reyes et al. (2010); Gupta and Garg (2012); Roessler and Abele (2013); Andersson and Bellgran (2015); Roessler and Abele (2015); Domingo and Aguado (2015); Sahu et al. (2015); Mansor et al. (2015); Shakil and Parvez (2020) |
| Studies that evaluate OEE and explore the different approaches to loss classification or calculation | Jeong and Phillips (2001); Huang et al. (2003); De Ron and Rooda (2006); Muchiri and Pintelon (2008); Hubl and Gmainer (2008); Badiger and Gandhinathan (2008); Zammori et al. (2011); Singh et al. (2013); Puvanasvaran (2013); Garza-Reyes (2015); Hedman et al. (2016); Yalagi et al. (2016); Ylipää et al. (2016); Fekri and Avakh Darestani (2019) |

Table 2: Summary and categorisation of OEE research

## 2.2 Total Productive Maintenance (TPM)

As discussed by Mishra et al. (2008), TPM is not an entirely new idea, and is considered the natural consequential step in maintenance practice's evolution. It is mainly based on preventive maintenance theory and its techniques and methods that have been initially introduced in Japan, providing a thorough life cycle approach to the management of equipment that minimises production losses (Gupta and Garg, 2012). TPM aims to maximize equipment effectiveness, by improving an equipment's function and design, in order to optimally utilize companies' hardware (Mishra et al., 2008). Moreover, it is a labour-intensive maintenance system, which involves all departments and employees in a firm (Jeong and Phillips, 2001; Mishra et al., 2008). It enables production managers to optimize their manufacturing processes, by producing products with good quality while maintaining a high-level of customer satisfaction; this allows companies to benefit from several competitive advantages and as a result, reap greater profits (Ahuja and Khamba, 2008; Bon et al., 2012). Evidence of TPM initiatives' effectiveness has been explored in previous studies, showing a reduction in machine breakdown frequency, defects, and other production losses, which potentially saves companies millions of dollars (Huang et al., 2003; Gupta and Vardhan, 2016). In the preliminary stages, TPM efforts are directed towards the identification and analysis of the six major losses, which are considered significantly responsible for lowering equipment effectiveness (Ahuja and Khamba, 2008). Overall Equipment Effectiveness (OEE) is mainly used as a measure to assess the effects of TPM activities (Bon et al., 2011).

Performance measurement is a significant prerequisite for the realisation of true continuous improvement of processes; hence, it is imperative for production managers to establish and utilize the needed metrics for production data collection and analysis (Gupta and Garg, 2012). TPM utilizes OEE as a quantitative measurement system of a production process' performance, determining the success of failure or TPM initiatives (Jeong and Phillips, 2001; Huang et al., 2003). Generically, OEE is capable of representing the combination of the maintenance, management, and availability of equipment and resources (Gupta and Garg, 2012). OEE is highly recognized in nearly all TPM-implemented industries (Gupta and Vardhan, 2016); this, in return, complements the explicit connection between TPM with OEE, and continuous improvement as it enables the effective implementation of TPM, and as a result the fostering of a lean culture (Binti Aminuddin et al., 2016). Even though, OEE was first introduced as part of TPM, its usage has evolved past the maintenance paradigm, where it has also been used extensively for the optimization of machine productivity (Kuman and Soni, 2014).

## 2.3 Overall Equipment Effectiveness (OEE)

Before the advent of OEE, only availability was considered in equipment utilization, which resulted in the constant overestimation of equipment utilization (Ljungberg, 1998). OEE methodology assists production managers optimize equipment effectiveness and reduce cost of ownership, through incorporating a set of manufacturing performance key indicators (Huang et al., 2003). This section will first introduce OEE, then present a conceptual model depicting OEE's evaluation mechanism, followed by identifying its indicators, consequently defining the six big losses, thereupon OEE's evolution and data collection process is discussed.

### 2.3.1 Introduction to OEE

The primary goal of OEE is not to get the optimum measure, but to get a simple measure, yet still accurate enough, that indicates where improvement resources should be allocated (Jonsson and Lesshammar, 1999). OEE identifies six losses that it aims to eliminate in order to maximize the valuable operating time of a process; it is a bottom-up approach where autonomous small groups on the shop-floor strive to achieve the highest attainable OEE value (Muchiri and Pintelon, 2008; Jonsson and Lesshammar, 1999). These losses, as defined by most reviewed literature, are equipment failure, setup and adjustments, idling and minor stoppages, reduced speed, defects in process, and reduced yield (Hubl and Gmainer, 2008). OEE is calculated by multiplying availability, performance, and quality rates (Mahmood et al., 2016), as can be seen in figure 1.

| | Nakajima (1988) | De Groote (1995) |
|---|---|---|
| Availability (A) | $\frac{\text{Loading time} - \text{downtime}}{\text{Loading time}}$ | $\frac{\text{Planned production time} - \text{unplanned downtime}}{\text{Planned production time}}$ |
| Performance (P) | $\frac{\text{Ideal cycle time} \cdot \text{output}}{\text{Operating time}}$ | $\frac{\text{Actual amount of production}}{\text{Planned amount of production}}$ |
| Quality (Q) | $\frac{\text{Input} - \text{volume of quality defects}}{\text{Input}}$ | $\frac{\text{Actual amount of production} - \text{non-accepted amount}}{\text{Actual amount}}$ |
| OEE | $(A) \cdot (P) \cdot (Q)$ | $(A) \cdot (P) \cdot (Q)$ |

Figure 2: OEE Definitions (Jonsson and Leeshammar, 1999)

It is most suitable for integrated machinery systems in mass-production environments where customer demand is not the constraint of the system, as defined by the theory of constraints (TOC) by targeting the bottleneck processes and improving its asset utilization and productivity (De Ron and Rooda, 2006; Hubl and Gmain, 2008). Yalagi et al. (2016) argue that OEE helps reduce downtime costs, repairs costs, labor inefficiencies, quality costs, and increase both personnel productivity and production capability. Moreover, it may be applied to any individual work center, or rolled up to department or plant levels for internal and external benchmarking and identification of the worst machine performance to dedicate TPM efforts and activities to (Hubl and Gmainer, 2008; Dal et al., 2000; Mahmood et al., 2016). It also has measurable benefits that significantly improve the bottom line of production operations, enhancing companies' competitive edge (Muchiri Pintelon, 2008).

### 2.3.2 Conceptual Model

A conceptual model displaying the OEE evaluation mechanism dynamics can be found below (Figure 3). A circular arrow end corresponds to a positive correlation between the variables, and a square arrow end represents a negative correlation. The Six Big Losses directly affect three main branches of losses: downtime, speed, and defect losses. In return, these affect the valuable operating time, which consequently alters the availability, performance, and quality rates. Due to the OEE being used as an indication of TPM improvements (Ljungberg, 1998; Kwon and Lee, 2004; Ahuja and Khamba, 2008; Gupta and Garg, 2012; Mahmood et al., 2016), the model is extended from the OEE elements (availability, performance, and quality) to emphasize OEE's significance as a TPM performance improvement indicator.

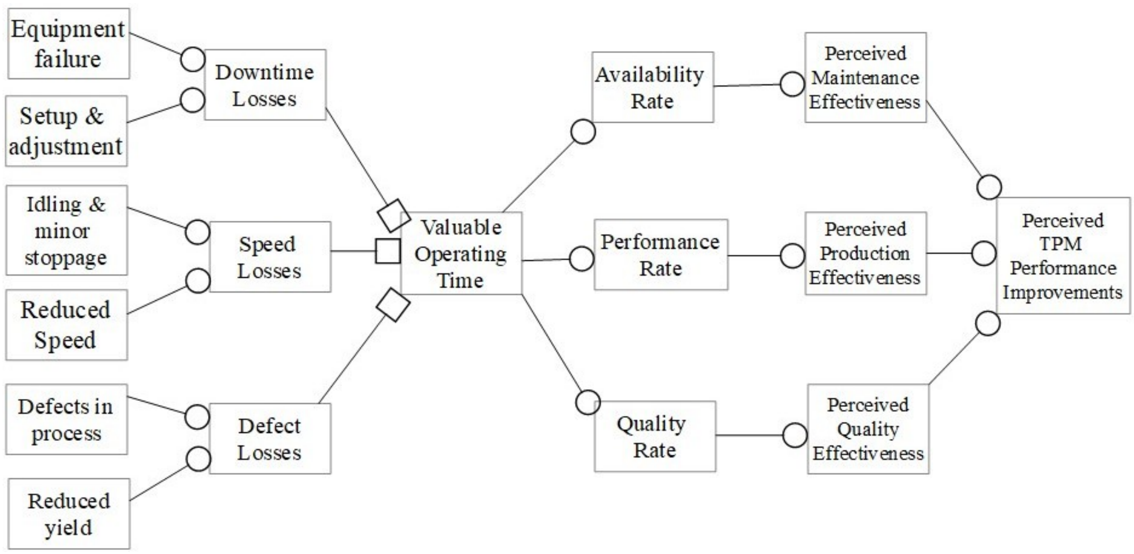



Figure 3: OEE Evaluation Mechanism

### 2.3.3 OEE Indicators

The OEE measurement is a function of three variables: availability, performance, and quality rates as discussed by Yalagi et al. (2016). The availability rate of this metric accounts for the percentage of time in which the machine is available to operate. Its exclusion of the effects of performance, quality, and planned downtime deems it a pure measurement of up time. It is determined by dividing the operating time by the planned production time, usually referred to as loading time (Figure 2). When the downtime losses sum up to zero, the availability becomes 100% or 1. 100 percent availability implies that the process under examination runs without any recorded disturbances or stops, during the time of analysis.

The performance portion of the OEE metric includes speed losses. Performance is computed by dividing the net operating time by the operating time, representing the percentage at which the equipment runs in contrast to a predefined optimum measurement. This part of the metric excludes the effects of availability and quality related losses, meaning it is not penalized for rejects, for instance. It can also be computed by dividing the product of the ideal cycle time and total number of units produced by the operating time (Figure 2). Ideal cycle time is the minimum amount of time required for a process to start and finish with optimal conditions. As with availability, performance is capped at 100 percent, and if reached, it is an indication that the equipment has been consistently working at its optimum speed.

The quality metric is responsible for determining the percentage of good units produced of the total pieces produced. It excludes the effects of both former metrics, making it a pure measurement of process yield. To calculate the quality rate, the valuable operating time is divided by the net operating time. Another way to compute this is by the quotient of good unit produced and total amount of unit that were being produced. As with its former rates, it cannot exceed 100%; a 100 percent quality rate indicates that no units have been rendered defected or needed rework. These three performance indicators facilitate the OEE Factors method to take place by multiplying the three rates, to finally attain an OEE value (Figure 2).

### 2.3.4 Six Big Losses

Nakajima (1989) defines the six big losses as equipment failure, setup and adjustment, idling and minor stoppages, reduced speed, defects in process, and reduced yield (Hedman et al., 2016). These sources of wastes can be classified as chronic or sporadic disturbances, occurrences in which resources are being consumed without adding value. OEE aims to identify these losses, using a bottom-up approach where the entire work force seeks maintaining a high OEE level by continuously eliminating the six big losses. It is however important to note that the exact definitions of OEE and the six big losses differs between authors and applications (Bamber et al., 2003). Below is a brief summary of the widely-accepted and cited definitions of each loss.

*Breakdown Losses*

Bamber et al. (2003), Kumar and Soni (2014), and Hedman et al. (2016) categorize breakdown losses as time losses that hinder productivity, and quantity losses as a result of products being rendered defective.

*Setup and adjustments*

Kumar and Soni (2014) define setup and adjustment as time losses that occur as a consequence of downtime and defective products, in order to accommodate the production requirements of another item to be produced, following the end of production of a certain item (Bamber et al., 2003; Hedman et al., 2016).

*Idling and minor stoppages*

Idling and minor stop losses are defined as wastes that occur because of the halt or interruption of production by a temporary malfunction or when an equipment is idle (Bamber et al., 2003; Kumar and Soni, 2014; Hedman et al., 2016).

*Reduced speed*

Reduced speed refers to the difference between ideal or expected speed of production or processing time and the actual operating speed (Bamber et al., 2003; Kumar and Soni, 2014; Hedman et al., 2016).

*Defects in process*

Quality defects and rework losses can be simply defined as losses in quality caused by malfunctioning of production machinery (Bamber et al., 2003; Kumar and Soni, 2014; Hedman et al., 2016).

*Reduced yield*

Reduced yield refers to start-up losses that occur in the early stages of production from machine startup to, and until, stabilization (Bamber et al., 2003; Kumar and Soni, 2014; Hedman et al., 2016).

### 2.3.5 OEE Evolution

Several efforts were made by many researchers to develop OEE with the aim to mitigate the insufficiency of the OEE tool to cover a broader perspective as deemed important in the production system (Muchiri Pintelon, 2008). The OEE tool's definition has evolved in literature to different other terms in order to broaden its scope of application, evolving into overall factory effectiveness (OFE), overall plant effectiveness (OPE), overall throughput effectiveness (OTE), production equipment effectiveness (PEE), overall asset effectiveness (OAE), and total equipment effectiveness performance (TEEP). Figure 4, attached below, displays schematically the 'evolved' OEE metrics that have taken additional factors, losses, or approaches into account. An extensive literature review of OEE literature has highlighted the abundance of numerous derived methods for calculating OEE in order to satisfy the ever growing need of managers that require more holistic performance measures (Gibbons and Burgess, 2010). However, these new metrics have shifted away from the original calculation methodology (Gibbons and Burgess, 2010). Developing the OEE performance indicator further, this paper aims to discuss how OEE can be optimally used to overcome some of its criticisms sans departing from its primary calculation.

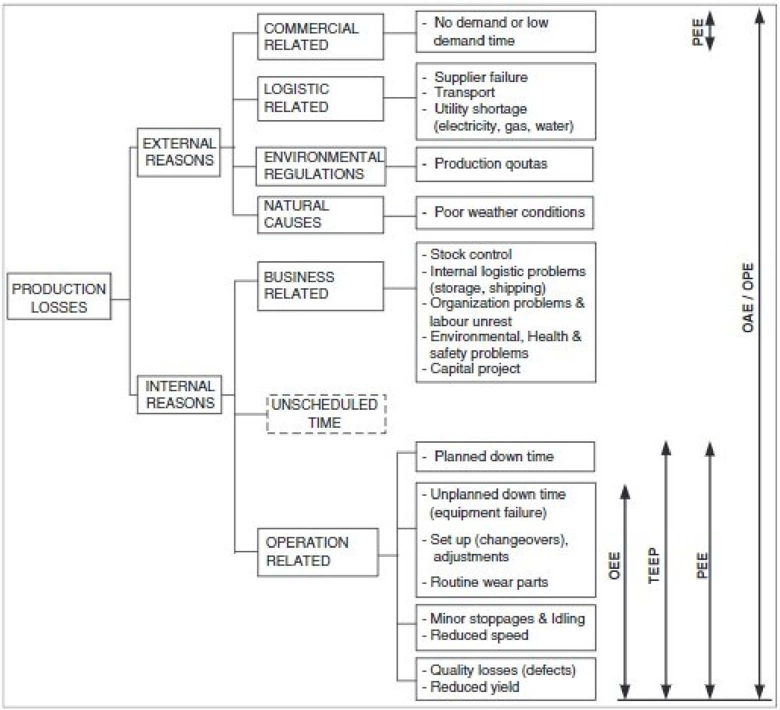



Figure 4: Classification of production losses for calculating overall production effectiveness (Muchiri and Pintelon, 2008)

### 2.3.6 Data Collection

In order to guarantee an accurate and reliable OEE measure that truly represents the performance of a process, is dependent on companies' data collection ability and the degree of accuracy required (Hedman et al., 2016). Arguably, the most crucial part in measuring OEE is the process of collecting and measuring accurate setup times (Mansor et al., 2015). Regardless of the formulas used for the OEE calculation, the key to fostering continuous process improvements is through optimizing the approach of data collection and classification (Jeong and Phillips, 2001; Bamber et al.„ 2003). The need for accuracy while measuring OEE has been highlighted by Jeong and Phillips (2001), Bamber et al. 2003), Muchiri and Pintelon (2008), Binti Aminuddin et al. (2016), and more.

Mansor et al. (2015) argue that without accurate data, the OEE measurement is rendered useless as it would not truly represent the process. The relevant data must be extracted in real time after a task has concluded, which requires a convenient and not too complex system to avoid recording errors (Roessler and Abele, 2013). Also, resistance from employees responsible for the data collection process has been widely cited, which leads to inaccuracies in the collected data, and as a result a drop in employee morale. This, in return, threatens the effective implementation of OEE as a TPM tool, implying that management has a key role in managing its implementation by synthesizing operator assistance and data collection automation to ensure data collection in an accurate and timely fashion (Binti Aminuddin et al., 2016).

To ensure significant improvements in the data collection process needed to calculate OEE, plant data acquisition systems can be employed, or for less capital-intensive machinery manually through operator logs (Roessler and Abele, 2013). In some cases, a plant data collection system is utilized with partial assistance from operators, rendering the data collection process semi-automatic. Automated data collection has been tested and proven to provide a high degree of accuracy and reliability, resulting in more performance improvements (Binti Aminuddin et al., 2016). Bamber et al. (2003) have seen immense improvements in equipment performance of companies that use a consistent measurement methodology for determining the six big losses and company-specific method of calculating OEE. Finally, it is important to emphasize that the data recording process itself may lead to process disruptions if operators are overburdened in the case of a rise of the frequency of short-term disruptions that take place throughout the shift (Roessler and Abele, 2013).

# 3 SWOT Analysis

A SWOT analysis has been chosen to be the focal study method of this research as a means to diagnose, assess, and essentially provide room for further research to develop the key figure OEE. This technique traditionally appears to have been originated as a product of corporate management literature efforts, specifically at Stanford Research Institute. It was developed as a tool to assist in dissecting the underlying reasons behind business planning failure. SWOT is an acronym for an organization's internal strengths and weaknesses, in addition to its external opportunities, and threats. Moreover, it is considered a key business tool, claiming the title 'design school model' as it aims to use the assessment of a corporation's strengths, weaknesses, opportunities, and threats, enabling strategic formulation (Mishra et al., 2008).

SWOT has been used as a key tool in previously conducted research, ranging all the way back to the 1980s. In agreement with SWOT's advocates, 'strengths' correspond to ingrained competencies, while 'weaknesses' refer to intrinsic drawbacks that inhibit performance. In contrast, 'opportunities' identify the potential for improvement or growth, whilst 'threats' express the external barriers that repress strengths, accommodate weaknesses, and impede opportunities. Undoubtedly, a precondition for success can be attributed to utilizing strengths and threats in order to realize opportunities and unlock further capabilities, overcoming inherent weaknesses. The four aforementioned elements of SWOT are defined in literature for general-use as shown below (Table 3):

| | |
|---|---|
| *Strengths:* A resource or capacity the organisation can use effectively to achieve its objectives. | *Weaknesses:* A limitation, fault or defect in the organisation that will keep it from achieving objectives. |
| *Opportunities:* Any favourable situation in the organisation's environment. | *Threats:* An unfavourable situation in the organisation's environment that is potentially damaging to its strategy. |

Table 3: (Mishra et al., 2008)

However, in order to guarantee the optimum use and adoption of this tool to adequately assess and examine the OEE metric, it has been adapted as follows (Table 4):

| | |
|---|---|
| *Strengths:* If OEE has a unique characteristic when compared to other performance measurement systems, then it is considered as a strength of OEE. | *Weaknesses:* If important elements or functions that OEE lacks or fails to perform, then it is considered a weakness. |
| *Opportunities:* Represent the potential room for improvement or scope expansion of OEE's current calculation methodology and its indirect positive effects on overall business performance for instance. | *Threats:* Outline the set of perils that may implicate OEE, deeming it unsuitable for certain uses, potentially affecting operations negatively. |

Table 4: SWOT elements stipulative definitions

Based on this precise interpretation of the different factors of the SWOT analysis, strengths, weaknesses, opportunities, and threats of OEE are identified. The SWOT analysis is carried out in the following subsections.

## 3.1 Strengths

OEE's widespread acceptance in the business world is due to the immense value it offers its users with regard to improving equipment effectiveness by cutting down on unnecessary non-value added activities or losses, essentially improving production systems (Bamber et al., 2003). It is most suitable for integrated machinery systems in mass-production environments (Ljunberg, 1998; De Ron and Rooda, 2006), combining all targets of TPM in one metric (Ljungberg, 1998; Hubl and Gmainer, 2008). Moreover, it categorizes major losses or reasons for poor performance, providing the basis for identification of improvement priorities and initiation of root cause analysis, by pointing out hidden capacity in a manufacturing process and enables having a balanced flow, and tracking and tracing improvements or decline in equipment effectiveness over time (Muchiri and Pintelon, 2008; Yalagi et al., 2016). This contributes to the reduction of process variability, changeover times, overtime expenditure, improves operator performance, and allows the deferral of major capital investment as a result of optimizing machine utilization and unleashing hidden capacity (Muchiri and Pintelon, 2008). Also, it provides systematic analyses of equipment utilization, quality, and efficiency, synthesizing performance measurements with business objectives through the reduction of non-value added activities (Ferko and Znidarsic, 2007; Singh et al., 2013).

In addition, the OEE metric allows companies to improve their competitiveness, both internally and externally, because it is somewhat easy to compare different equipment units acting as a good measure for benchmarking (Hubl and Gmainer, 2008; Hubl et al., 2009; Gupta and Vardhan, 2016). (Hubl et al., 2009; Hubl and Gmainer, 2008) further elaborate on OEE's benefits, claiming that using OEE as a performance measurement facilitates the improvement of bottleneck performances, benefiting the production output of the entire system. Further, OEE reflects performance from various dimensions: availability, quality, and performance, utilizing simple and thorough visualization of information (Mahmood et al., 2016). OEE is considered a simple, yet comprehensive, measure of equipment effectiveness (Jonsson and Lesshammar, 1999) that improves total asset performance and reliability (Gupta and Vardhan, 2016). Mahmood et al. (2016) assert OEE as the starting point for productivity optimization and the drive towards operational excellence.

## 3.2 Weaknesses

Like any other existing business metric, OEE suffers from a number of pitfalls that have implications of great magnitudes as briefly discussed in chapter 1, creating the urgency and need for this paper and other further research efforts, in order to optimize this key figure. For starters, OEE is not a good performance measurement for stand-alone equipment (De Ron and Rooda, 2006). This same weakness is challenged and contradicted by other researchers who claim that one of the drawbacks of OEE is that it is only capable of describing the productivity behaviour of individual machines (Muchiri and Pintelon, 2008). Another issue is resultant from the existence of common confusion in literature whether OEE measures effectiveness or efficiency of machinery (Muchiri and Pintelon, 2008). Furthermore, using OEE for benchmarking purposes is complicated and many difficulties may arise while attempting to do so (Hubl and Gmainer, 2008); this can be attributed to the abundance of different OEE definitions in literature and other varying circumstances between companies, making it burdensome to identify optimum OEE figures and therefore difficult to compare OEE between firms, shops, and stand-alone machines (Jonsson and Lesshammar, 1999; De Ron and Rooda, 2006; Hedman et al., 2016).

Arguably, the most pressing issue with OEE as a performance measurement system is that it leaves out some factors that affect capacity utilization such as planned downtime, lack of material and labour resources, breaks in production schedule, precautionary resting times, and daily shop floor meetings (Ljungberg, 1998; Hubl et al., 2009), creating the need for a more appropriate time basis (De Ron and Rooda, 2006). (Ljungberg, 1998) discusses the omission of significant types of losses due to the OEE evaluation method, for example major losses due to setup and adjustments are usually regarded as productive time as opposed to being treated as losses. Also, only quality losses within the defined system under evaluation are taken into consideration (Jonsson and Lesshammar, 1999). Adding to these complications, there is no accepted consensus with respect to the magnitude and classification of different types of losses and the underlying reasons for their occurrence. This is seen whilst examining OEE's limitation when it comes to indicating the influence of downtime and rework on the valuable operating time, for instance (De

Ron and Rooda, 2006).

Moreover, some important measures are not accounted for in the OEE calculation such as cost, flexibility, usability, market demand, etc. which requires OEE to be complemented by other performance measuring tools (Jonsson and Lesshammar, 1999; Muchiri and Pintelon, 2008; Hubl et al., 2009). OEE renders a product acceptable solely based on quality requirements (Hubl et al., 2009), without evaluating whether the right product is produced at the right time (Hubl and Gmainer, 2008). As a performance measurement system, its use is not appropriate for situations where the market demand is the constraint for the production system as defined by the theory of constraints (TOC) (Hubl et al., 2009), low-volume job shops and some bath processes (Muchiri and Pintelon, 2008), and non-bottleneck processes (Hubl and Gmainer, 2008). It seems that the OEE calculation method is not effective when employed in oil, gas, and petrochemical prcoesses (Fekri and Avakh Darestani, 2019). Being a deterministic measurement, OEE is not equipped to recognize the variability of a process, which is a rather important drawback as variability is one of the main causes of wastes (Zammori et al., 2011). Also, it requires certain parameters to be constants, such as investment, cycle times, etc. (Hubl and Gmainer, 2008). In practice, a high degree of complexity and lack of continuous improvement is witnessed due to the incorrect use and implementation of OEE (Muchiri and Pintelon, 2008); companies' missions is usually too focused on results and not on the improvement (TPM) activities itself that are taking place (Ljungberg, 1998).

## 3.3 Opportunities

OEE provides its users with a broad range of opportunities as both an effective performance measurement system and as a driver for continuous improvements in a company's production line. The OEE metric initiates the development of quantitative variables, linking maintenance measurement to corporate strategy (Ahuja and Khamba, 2008). It has the potential to improve the production output of the entire production plant, via targeting bottleneck processes (Hubl et al., 2009). Also, it may be applied to any individual work center, or rolled up to department or plant levels for internal and external benchmarking and identification of the worst machine performance to dedicate TPM efforts and activities to (Dal et al., 2000; Hubl and Gmainer, 2008; Mahmood et al., 2016). Hubl and Gmainer (2008) also argue that OEE assists companies in avoiding unnecessary purchase due to better usage of operating assets, facilitating the maximising of productivity via evading extra shifts, while creating capacity for extra shifts and maximizing return on investment for major capital equipment.

As discussed in earlier sections, OEE serves as an indicator of process improvement activities, specifically TPM and lean initiatives, within the manufacturing environment

(Ng et al., 2014). (Dal et al., 2000; Ng et al., 2014) argue that applying lean Six Sigma methodology has enhanced the performance and OEE, improving the overall manufacturing performances. Moreover, it has measurable benefits that significantly improve the bottom line of production operations, enhancing companies' competitive edge (Muchiri and Pintelon, 2008). Further research is needed to truly unravel the dynamics of translating equipment effectiveness in terms of cost; this will result in even more value and significance to management (Muchiri Pintelon, 2008). Other available opportunities for the use of OEE exists in combination with an open and decentralized organization design could improve several production weaknesses; when *"applied by autonomous small groups on the shop-floor together with quality control tools, it is an important complement to the traditional top-down oriented performance measurement systems"* (Jonsson and Lesshammar, 1999; Ahuja and Khamba, 2008). Also, dividing availability losses into stops due to and not due to machine failure made the status of losses more clear and simplified the analysis (Jonsson and Lesshammar, 1999).

The use of technology, a simulation as a tool for instance, for analysing losses offers further room for flexible OEE use and benefit (ljunberg, 1998). The losses taking a large part of production capacity should be focused on and further divided into sub-groups. The use of automated production data acquisition (PDA) for collecting and categorizing losses has been proven to achieve high accuracy and reliability (Hubl and Gmainer, 2008). (ljunberg, 1998) argue that the design of the data collection form or method should be carried out with cooperation from the operators responsible for actually using it. Computerised systems for collecting OEE can be really accurate, but tend to be difficult to assess the underlying reasons for failure; a combination of both automatic and manual data collection could prove to be optimal (ljunberg, 1998).

Kumar and Soni (2014) identify the following as strategies for potentially improving the OEE metric: training shop floor operators, regular measurement and analysis of OEE, performance monitoring using OEE, and benchmarking against a desired OEE value. Several authors have explored the advantages of using OEE with some lean initiatives and tools, such as 5-WHYs (Benjamin et al., 2015), 5S (Sahu et al., 2015), Single-Minute Exchange of Die or SMED (Mansor et al., 2015), and Value-stream mapping or VSM (Shakil and Parvez, 2020).

## 3.4 Threats

Aside from OEE's opportunities, several threats can be identified that may deem OEE usage unsuitable for certain purposes, potentially becoming counterproductive, affecting operations negatively. For instance, if used for purposes other than a measure of equipment effectiveness, it has potential negative implications on logistical drivers, such as lead-time, inventory, and delivery reliability (Hubl and Gmainer, 2008). Also, when the conditions between two production systems are not the same, wrong conclusions may be drawn if OEE is used as a benchmark for comparisons; so, awareness of using OEE as a benchmark measure is crucial (Hubl and Gmainer, 2008; Hubl et al., 2009). The lack of cross-functional teams (operation, maintenance, and management) may hinder the ability to effectively utilize the OEE measurement to materialize continuous improvements in bottleneck processes (Bamber et al., 2003; Ahuja and Khamba, 2008; Sivaselvam and Gajendran, 2014).

In practice, while using OEE, most companies focus on downtime losses, especially breakdowns, whilst many losses like planned downtime, cycle time losses, and minor stoppages are not addressed or accounted for (Hubl and Gmainer, 2008; Benjamin et al., 2015). (Muchiri and Pintelon, 2008) also shed light on this problem that in practice, specialized attention of important losses was lacking or left out completely. Ljunberg (1998) discusses the lack of focus of companies on performance losses whilst conducting OEE analyses for their equipment. Performance losses are, in certain situations, difficult to define and eliminate, whilst making up a large proportion of the total downtime (Jonsson and Lesshammar, 1999; Benjamin et al., 2015). The root cause of this issue stems from the fact that measuring the actual cycle time is challenging for several businesses, especially when the same production equipment are used to process or manufacture different products. This is significant due to the importance of the identification of the weight and underlying causes for losses, allowing the TPM activities to optimally solve the major losses (Ljunerg, 1998).

Furthermore, loopholes for increasing the OEE measurement for production systems exist, even if no actual improvements take place (Hubl and Gmainer, 2008). The problem of monitoring only the good parts is that the logistic key figure, lead time, utilization and inventory levels can get worse (Hubl et al., 2009). It is possible to increase OEE value of a production system by increasing lot sizes; however, this results in lower delivery reliability, and an increase both tied-up capital and throughput time (Hubl and Gmainer, 2008). Moreover, the quality rate measurement is considered general and brief; however, a more specific definition of the quality parameter would decrease the simplicity of the metric, which goes against the predefined stakes in the previous subsection (Jonsson and Lesshammar, 1999). In practice, there is usually a lack of coordination in deploying available resources (labour, information systems, and tools) to manage production efficiently (Muchiri and Pintelon, 2008). Also, inflexible working schemes will hinder the use of OEE as a TPM tool (Hubl et al., 2009).

Finally, data gathering and analysis treats exist which highly risk OEE's reliability as a performance measurement system. If data is calculated manually, there is risk of losses not being categorized properly or at all, which makes it harder to optimally solve the problems in the process or machinery under examination (Hubl and Gmainer, 2008). Sometimes the operators believe that some disturbances have a major impact on the OEE measurement, later analysis can show that this was completely wrong; on the other hand, there are times that completely different views of the pattern of disturbances are witnesses by different stakeholders (Ljunerg, 1998). In many industries, a resistance from operators and foremen against data collection can be seen (Ljunerg, 1998). This is considered a major threat as the reliability of OEE is highly dependent on the quality of the collected data (De Ron and Rooda, 2006). Other common threats that may hinder OEE's accuracy and effective use are human perturbation in the recording process, discrepancies in loss classification, missing recognition of sporadic losses due to limited data capturing time window (Roessler and Abele, 2013; 2015).

## 3.5 Discussion

Upon exploring and evaluating the different characteristics of OEE, it was found that its definition, condition for use, purpose, calculation methodology, and scope of application differ slightly in both literature and in practice. This presents a problem for managers and practitioners, when they decide to use OEE as a key TPM metric to improve their production processes. Since, choosing and implementing optimum performance measurement systems is a crucial aspect of any production line's success, this is an urgent issue that needs to be addressed further. Hence, this paper conducts a SWOT analysis of the different aspects of OEE, namely, its strengths, weaknesses, opportunities, and threats. Based on the analysis, it was evident that OEE as a TPM key performance metric has its own strengths and weaknesses. It can also be concluded that the implementation of OEE is absolutely not a simple task, as it is heavily limited by weaknesses and threats; however, if businesses can optimally integrate and use OEE in their processes, it can potentially provide considerable strengths and opportunities in order to attain a competitive edge (Mishra et al., 2008).

In order to overcome some of the weaknesses and minimize the threats of OEE, several research efforts have been dedicated (Table 2) to expanding the scope of OEE by enlarging its purpose or through the inclusion of more elements of performance other than availability, performance, and quality. In addition to this, other studies were conducted to understand and explore the relationship between OEE with other performance measures or approaches, while other researchers attempted to evaluate OEE and explore the different approaches to loss classification or calculation. Below is a brief summary of some of the significant research findings and products that have been published in the past two decades.

- (Ljunberg, 1998) used and tested a two-step model that can be used to ease the process of data collection; also further optimization of the data collection procedure was proposed to solve this issue as well.

- Oechsner et al. (2003) expanded the OEE metric to overall factory effectiveness (OFE), that is designed to focus on the plant-wide picture. It takes into account the OEE factors, in addition to responsiveness, costs, and technological changes.
- Kwon and Lee (2004) developed a model estimating the quantitative monetary managerial effects by cause of TPM activties, by *"calculating the monetary total sum saved composed of contribution of profit and saving costs that are obtained by improving the OEE"*.
- (De Ron and Rooda, 2006) developed a metric that is suitable for measuring equipment effectiveness, EE, for standalone machines, whilst reporting the influence of downtime and rework.
- Badiger and Gandhinathan (2008) introduced a new OEE metric, with a fourth element: usability.
- Muchiri and Pintelon (2008) provided an overview of the different versions of OEE, such as OFE, overall plant effectiveness (OPE), overall throughput effectiveness (OTE), production equipment effectiveness (OPE), overall asset effectiveness (OAE), and total equipment effectiveness performance (TEEP). These metrics have been developed to include more losses that the original OEE did not account for.
- (Hubl et al., 2009) developed the OEE metric, which takes into account market demanded production,focusing on both the effective use of equipment and on customer demand, making it able to identify changes in the customer demand.
- Gibbons and Burgess (2010) proposed an OOE framework, with an enhanced availability element, having three additional measures: reliability, maintainability, and overall asset management effectiveness.
- Wudhikarn et al. (2010) rectfied the weaknesses of (Kwon and Lee, 2004), by showing all production elements' losses in monetary unit not only just overall loss.
- Zammori et al, (2011) presented a stochastic methdology of OEE, as opposed to its deterministic nature, evolving OEE to take variability in its calculation.
- Samat et al. (2012) integrated OEE with the reliability principle, proposing an equipment performance and reliability model based on equipment effectiveness.
- (Roessler and Abele, 2013; 2015) proposes an OEE metric that takes into account variability by combining the fuzzy set theory and OEE.

- Garza-Reyes (2015) presents a new metric derived from OEE, overall resource effectiveness (ORE), which takes into acount the three OEE elements and other performance parameters: the efficient use of raw materials and the production environment.
- Domingo and Aguado (2015) integrated sustainbility and OEE, producing a metric of lean and green manufacturing systems, overall environmental equipment effectiveness (OEEE), allowing sustainability to be included in decision-making.
- (Mahmood et al., 2016) developed an OEE analyzing tool that helps in identification of root causes, determines the weakest area or hurdle in a machine's optimal performance, and helps to find out how much overtime is being performed against the time lost due to availability, performance, and quality issues.
- Yalagi et al. (2016) added one more factor in OEE calculation, usability. This allows a higher degree of analysis of losses and facilitates setting up the initiatives to tackle these losses.
- Che Maideen et al. (2017) proposed a top-down framework to evaluate current performance of the machine using OEE, as opposed to its current status as a bottom-up approach.
- Puvanasvaran et al. (2019) integrated the Maynard Operation Sequence Technique (MOST) to the OEE calculation to develop an alternative OEE method, "*introducing two new factors, usability and human factor that distinguish setup losses into the frequency of the setup process and excessive work performed by workers*."
- Cheah et al. (2020) introduce an integrated OEE framework, outlining a set of guidelines for OEE improvement activities' implementation, with loss prioritization and benchmarking aspects.

As could be seen, immense efforts are being dedicated towards optimizing OEE as key performance indicator in the manufacturing industry. However, the amount of OEE's weaknesses and threats discussed throughout the chapter is a lot for one research to address. Consequently, all previously conducted research papers have aimed at contributing to the solution of an issue or a set of issues that OEE faces. As such, this research is highly influenced by the findings of Badiger and Gandhinathan (2008), Yalagi et al. (2016), and Puvanasvaran et al. (2019) who all attempted incorporating the extra element 'usability' in their newly proposed OEE calculation methodologies. Likewise, Hubl et al. (2009) is used as another cornerstone journal article due to its great value in their efforts to integrate the market into the original OEE metric.

# 4 Proposed OEE Calculation Methodology

TPM efforts are dedicated towards addressing major losses that take place in a production process, and its associated wastes by implementing and fostering an environment of continuous and systematic evaluations, and thereby improvement in companies' manufacturing processes (Ahuja and Khamba, 2008). OEE is used in practice as a driver for such performance improvement activities through diagnosing quality, productivity and machine utilisation issues and, in return, contributes to decreasing wastes often inherent in manufacturing processes (Bamber et al., 2003). As discussed earlier, OEE does not identify specific reasons why a machine is not operating optimally; however, it contributes in classifying the different areas that prompt improvements in the subjected process. As reviewed in chapter 2, Nakajima (1989) presented the original OEE metric where its availability element takes into account the total time that a machine is not operating due to breakdowns, setups and adjustments, and other stoppages. This way of categorizing losses merges all downtime events, both equipment- and process-related. This is a major drawback of OEE as it inhibits the a more detailed identification of losses (Badiger and Gandhinathan, 2008).

Even though different loss classifications ultimately should do not affect the final value of OEE, it is still of immense significance that specific definitions of the different OEE elements are addressed and aimed at delineating loss categorization further. This should be achieved while neither deeming the new OEE metric too complex for use nor deviating from OEE's original calculation methods as other researchers have done. Moreover, it was also deduced from the SWOT analysis that another major limitation of OEE lies in its inability to recognize changes in market demand (Hubl et al., 2009). This may potentially cost companies unnecessary resources due to certain logistical drivers not being managed properly, as a result of a lack of relevant and important process insights.

## 4.1 Two New Variables: Usability and Customer Requirement Rate

The newly proposed calculation methodology of OEE contrasts the original approach in that, two new factors called usability and customer requirement have been incorporated in the OEE calculation. The value of the usability factor stems from its ability to further categorize unplanned downtime occurrences into: equipment related downtime, needed for the calculation of the availability element of OEE and the stop time attributed to the production process, used to determine the usability element. The adoption of this factor results in more meticulous classifications of machinery and process losses that are formally associated to the availability element only. Within this context, equipment downtime is split into planned and unplanned stops, i.e. operational and induced stoppages. Furthermore, this new factor assists in identifying induced downtime losses more accurately, sans castigating the availability element of OEE. This allows the OEE metric to truly describe the availability factor of the machine under examination, enabling the assessment of both operational and induced time losses separately (Badiger and Gandhinathan, 2008).

The significance of the second proposed term, customer requirement rate, is that it includes the market in the OEE calculation as proposed by (Hubl et al., 2009). This mitigates one of the major limitations of OEE, the performance measurement's sole focus on acceptably produced products according to quality parameters without accounting for market demanded production. This is undergone via only considering the products that directly fulfill a customer order. This is important as it enables production managers to adjust their production plants' loading times based on the customer demand. Customer requirement losses can be defined as all activities in which production takes place for products that are yet to be assigned an owner; for example, production orders for restocking inventory levels or production of bigger batch sized than the customer requires due to technological and economic reasons. Upon subtracting the customer requirement losses from the valuable operating time of the original OEE method, the resultant is customer required operating time (CROT). The data required to assess the new OEE metric is discussed further in the ensuing sections, and Table 5 outlines the proposed classification of losses.

| OEE Element | Proposed Classification |
|---|---|
| Availability | Equipment Failure |
| Usability | Stop time<br>Stop time induced<br>Stop time operational |
| Performance | Idling and minor stops<br>Reduced speed |
| Quality | Defects in process<br>Reduced yield |
| Customer Requirement | Customer requirement loss |

Table 5: Proposed Loss Classification

## 4.2 Availability Rate

The availability rate can be computed by dividing the operating time (OT) by the loading time (LT).

$$AvailabilityRate = \frac{OT}{LT}$$

where,

- *LT = TotalAvailableTime - PlannedDowntime*
- *OT = (1 - (%ofEquipmentFailure/100)) * TotalAvailableTime - PlannedDowntime*

## 4.3 Usability

Usability is computed by dividing the running time (RT) by the OT (Badiger and Gandhinathan, 2008; Puvanasvaran et al., 2019).

$$Usability = \frac{RT}{OT}$$

### 4.3.1 Running Time

RT is determined by subtracting the stoppages that take place due to setup and adjustments from the OT.

$$RT = OT - (StopTimeOperational + StopTimeInduced)$$

where the stop times are defined by Badiger and Gandhinathan (2008) as follows:

- stop time operational includes functional activities such as changeovers, standard testing, planned material loading, and required documentation
- stop time induced is unplanned stop time, when the equipment is idle for reasons that cannot be accounted to the machine itself, but are due to external reasons like material, supply, and operator shortages

## 4.4 Performance Rate

The performance rate is calculated by dividing the net operating time (NOT) by the RT.

$$PerformanceRate = \frac{NOT}{RT}$$

where NOT can be computed by multiplying the quotient of the production output and actual cycle time (ACT) by the ideal cycle time (ICT) as demonstrated below (Hubl et al., 2009).

- *NOT = (OT/ACT) * ICT*

## 4.5 Quality Rate

The quality rate is computed by dividing the valuable operating time by the NOT.

$$QualityRate = \frac{VOT}{NOT}$$

The quality element can also be attained by subtracting the actual output during running time by rejects that require reworking, followed with dividing by the output.

$$QualityRate = \frac{ActualOutput - Rejects}{ActualOutput}$$

## 4.6 Requirement Rate

The last element is computed by determining the ratio between customer required operating time (CROT) and VOT, representing the quotient relationship between the actual output of the product process and the actual customer demand per unit (Hubl et al., 2009).

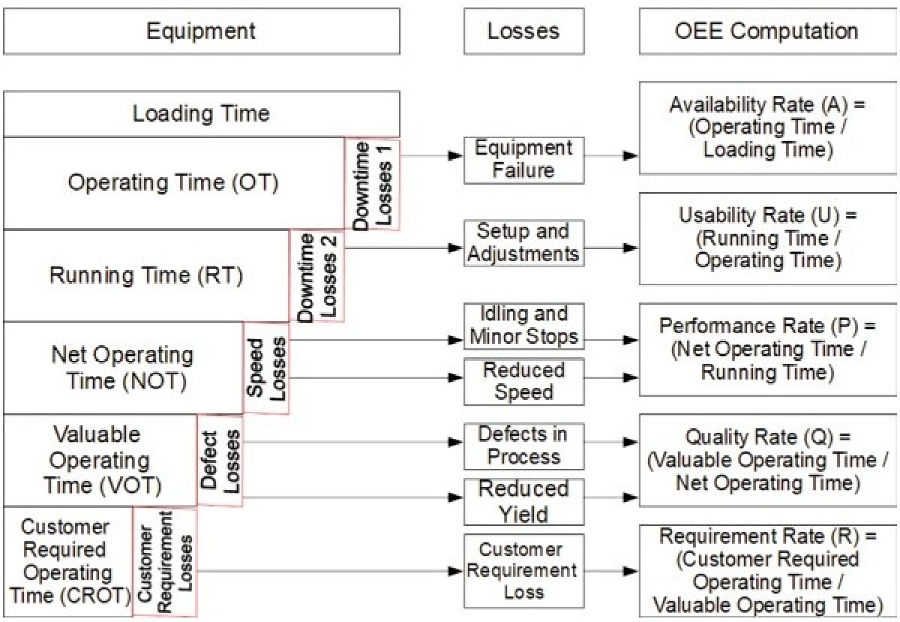
$$RequirementRate = \frac{CROT}{VOT}$$

where,

- *CROT = CustomerDemand * Ideal Cycle Time*

## 4.7 Modified Overall Equipment Effectiveness (OEE)

The proposed OEE calculation methodology is the product of availability, usability, performance, quality, and requirement rates. Figure 5 displays the new OEE calculation schema. It is also visible that OEE can be either computed straight away using the direct method, or through the OEE factors method where all rates are identified first then multiplied with one another.




$$OEE\ new = \frac{OT}{LT} * \frac{RT}{OT} * \frac{NOT}{RT} * \frac{VOT}{NOT} * \frac{CROT}{VOT} = \frac{CROT}{LT}$$

Figure 5: OEE new Calculation Schema

# 5 Research Design

To demonstrate the benefits of the proposed OEE new metric for measuring overall equipment effectiveness in a manufacturing setting, it was applied, tested, and compared with the original OEE calculation method using a one-machine model representing a generic real-world production line. Despite the conceptualization of the experiments that are conducted, the run numerical example's input values adequately resemble the characteristics of an actual production line in a manufacturing plant. Hence, the application of this paper's findings are validated and deemed reliable to a high degree beyond conceptual analysis. The purpose of this case study is to showcase the modified OEE and test its prevalence over the original method by using Microsoft Excel as utilized by Bon et al. (2011) and Hedman et al. (2016) in their data collection and analyses of their respective case studies in order to evaluate OEE. It being a deterministic value, OEE is not capable to account for process variability (Zammori et al., 2011), secluding the absolute necessity for applying this investigation to a modelled stochastic production line, which further justifies using deterministic numerical examples as opposed to stochastic process simulations. Even if stochastic models are used, it will rely on averages only for the analysis of the modelled system.

## 5.1 Model Description

In order to epitomize the proposed calculation methodology, a production plant of cutting tools is studied. This case study and the simulated data used were adopted and developed from Badiger and Gandhinathan (2008), Hubl et al. (2009), and Yalagi et al. (2016) due to the high resemblance of these research efforts' methodology and goal with this paper's attempt, expanding the scope of OEE in order to mitigate some of its drawbacks via the addition of extra elements. The manufacturing line treated is assumed to originally consist of the following subsequent processes: cutting, facing, centring, fluting and grinding. Each operation is characterized by different production capabilities, such as reliability and cycle times, requiring a synthesized set of models that illustrate the interactions between the different processes in order to assiduously examine the OEE of the different processes and of the entire production line as a whole. Consequently, a simplified one machine model is considered as the bottleneck process, fulfilling the purpose of this evaluation. This is validated as OEE's application is most suitable when dealing with one-machine bottleneck processes, as any process improvements made based on OEE analysis of a non-bottleneck process will not result in a higher overall manufacturing performance (Bamber et al., 2003; De Ron and Rooda, 2006; Hubl and Gmainer, 2008; Sivaselvam and Gajendran, 2014).

For the sake of simplicity, the model encompasses one process, representing all four aforementioned processes, that is responsible for transforming raw materials into finished goods. Upon a product's arrival in the finished goods inventory, it is deemed good or defected and cannot be reworked. To grasp the availability and usability factors, a shift time of 480 minutes is set. Moreover, in order to grasp the performance element, the ideal cycle time is specified to be 1.82 minutes, whilst the actual cycle time is modelled at 2.87 minutes. The quality losses resultant from defected products are 3.25 percent. The OEE evaluations employed in this study, use the approach of Nakajima (1989) for the original OEE calculation and the newly proposed OEE assessment methodology in Figure 5. Tables 6 and 7 summarize the input data used to classify the different losses for the calculating OEE using both methods, respectively. The calculations schemes modelled in MS-Excel can be seen in Appendix 1. There are two widely accepted calculation methods of OEE, the direct method and OEE factors method. The input data is the same for both methods, the difference lies in how the problem is approached (Yalgi et al., 2016). In this case, the OEE factors method is proposed as it offers a higher level of detail as opposed to the former technique which does not provide its users with insights regarding the behaviour and magnitude of different OEE losses and indicators.

| OEE Element | Nakajima (1989) | Time Simulated |
|---|---|---|
| Availability | Breakdown losses | 10% |
| | Setup and Adjustments | 3% |
| Performance | Idling and minor stoppages | 2% |
| | Reduced speed | ToBeComputed |
| Quality | Quality defects, rework, and yield losses | 3.25% |

Table 6: Input Values for Original OEE Loss Classification

| OEE new Element | Proposed Loss Classification | Time Simulated |
|---|---|---|
| Availability | Planned downtime | 10% |
| | Equipment Failure | 10% |
| Usability | Stop time induced | 12.5% |
| | Stop time operational | 12.5% |
| Performance | Idling and reduced speed | ToBeComputed |
| Quality | Defects losses | 3.25% |
| Customer Requirement | Unnecessary production | ToBeComputed |

Table 7: Input Values for Proposed OEE Loss Classification

## 5.2 Numerical Example: Three Cases

The value of including the usability element in the OEE calculation is demonstrated through the improved level of detail of loss classifications; this is elaborated upon in the next chapter. However, in order to underline the superiority of the modified OEE calculation over its former method as a result of the inclusion of the market, a short example is given containing three different hypothetical and subsequent cases: stable economic environment, a sudden drop in customer demanded products, and the result of production planning adaptation made by the production planners. Table 8 provides the controlled variables that were maintained as constants over all three cases. Table 9 shows the independent variables altered per stage to assist in underpinning one of the major drawbacks of the original OEE method, its lack of recognition of changes in crucial production parameters.

| **Controlled Variables** | **Value** |
|---|---|
| Shift Time (min) | 480 |
| Ideal Cycle Time (min) | 1.82 |
| Actual Cycle Time (min) | 2.87 |

Table 8: Controlled Variables

| **Independent Variables** | **Case 1** | **Case 2** | **Case 3** |
|---|---|---|---|
| Customer Demand (units) | 106 | 64 | 64 |
| Planned Downtime (min) | 80 | 80 | 80 + (0.045 * ShiftTime) |

Table 9: Independent Variables

In Case 1, no additional planned downtime is scheduled, and the customer demand is assumed to be constant. Next, the second case represents a sudden drop of customer demand by reducing the customer demanded products by 40% as done by Hubl et al. (2009). Finally, the third case has an increased planned downtime, equivelant to 4.5% of the scheduled shift time. This is to model possible adjustments to shift times as a result of customer demand reduction, resulting in a more suitable equipment loading time. In this numerical example, it is assumed that due to organizational constraints, the loading time can not be reduced past 18% (Hubl et al., 2009).

# 6 Results and Discussion

This chapter highlights the results obtained from the three-case numerical example undergone using both the original OEE calculation methodology and the proposed one. Consequently, the results are summarized and discussed, emphasizing the role and impact of the two newly added OEE indicators or elements.

## 6.1 Results

Table 10 and Figure 6 display the final OEE results per stage for both original and proposed OEE. As can be seen, the original OEE value remained constant throughout all three cases. This further emphasizes one of the main limitations of OEE, its lack of ability to account for changes in the market. Moreover, even the introduction of additional planned downtime did not affect the OEE measurement, which is yet another flaw of OEE that the proposed one mitigates. Figures 13 and 14 in appendices 2 and 3 respectively, display the results of the different OEE elements for both original and proposed methods using cluster charts to compare each indicator's behaviour per stage. While, figures 15 and 16 in appendix 4, summarizes the final OEE results in bar charts.

| **Dependent Variables** | **Case 1** | **Case 2** | **Case 3** |
|---|---|---|---|
| Availability | 0.87 | 0.87 | 0.87 |
| Performance | 0.634 | 0.634 | 0.634 |
| Quality | 0.968 | 0.968 | 0.968 |
| **OEE** | **53.4%** | **53.4%** | **53.4%** |
| Availability new | 0.88 | 0.88 | 0.873 |
| Usability | 0.659 | 0.659 | 0.637 |
| Performance new | 0.962 | 0.962 | 0.9958 |
| Quality new | 0.968 | 0.968 | 0.968 |
| Customer Requirement | 0.904 | 0.536 | 0.572 |
| **OEE new** | **48.8%** | **28.9%** | **30.7%** |

Table 10: Summary of Simulation Results

As opposed to the original OEE measurement, Figure 7 shows the proposed OEE value fluctuating between the three cases as the parameters customer demand and planned downtime are manipulated. In Stage 1, both original and proposed OEE values were somewhat similar. However, in the second case the proposed OEE is significantly reduced as a result of a sudden drop in customer demanded products. This is also intuitive because having less products demanded, results in equipment downtime, which in return will hinder equipment effectiveness. Finally, Case 3 demonstrates the result of production planning improvements on OEE. For instance, if the production manager recognizes that customer demand will remain low and incorporates this in the shift time or work schedule to adjust the loading time. The result is clear that the original OEE did not change yet again, while the proposed OEE witnessed a light increase.

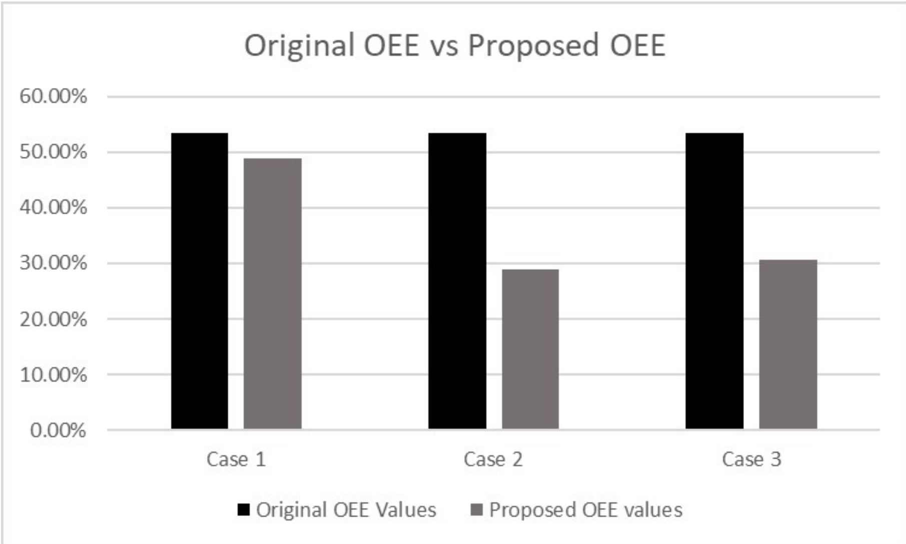



Figure 6: Bar Chart: Original vs Proposed OEE

## 6.2 Discussion

The value of adding the elements usability and customer requirement rate has proven to be potentially beneficial for OEE's maturity and evolution as a performance measurement system. Both the role and impact of both performance indicators are discussed further.

### 6.2.1 The Role and Impact of Usability

As discussed in previous chapters, one of OEE's main limitations lies in its classification and visualization of losses. Although, the original OEE accounts for six big losses, it has remained unsuccessful to identify areas of improvement effectively (Puvanasvaran et al., 2019). The addition of the usability element helps examine downtime losses, allowing a more specific analysis of losses (Yalagi et al., 2016). The proposed OEE accounts for both planned and unplanned stop time, providing an opportunity for addressing these losses independently, as opposed to simply considering them as unplanned downtime. The performance rate is a function of the running time (difference between operating time and stop time) rather than operating time (difference between loading time and unplanned downtime); hence, it truly represents the time in which the process is producing customer demanded products (Badiger and Gandhinathan, 2008).

Usability is utilized to measure the frequency of the setup and adjustment process in predefined time interval, differentiating setup losses from the original availability element of OEE, facilitating the user to identify the areas of improvement (Puvanasvaran et al., 2019). In addition, the setup and changeover losses are classified as stop time induced and stop time operational. This was done with the intention to further assist production teams to fully use OEE to help dedicate TPM efforts for setup and adjustment losses reduction. This can also motivate strategies for OEE users to reduce planned material loading, changeovers, shortage of materials, people, and information (Badiger and Gandhinathan, 2008). The numerical example results have shown how the proposed OEE encourages directing TPM initiatives on the usability factor of OEE due to its relatively low value, rather than the availability or performance rates. Therefore, the low OEE can be attributed mainly to equipment stop time induced and stop time operations, rather than equipment failure or breakdowns. Consequently, this serves as an opportunity for production managers to improve their processes. In this example, the stop time losses effect is dominant and examining it separately will help direct and steer process improvement efforts, focusing on the usability of equipment availability.

### 6.2.2 The Role and Impact of Customer Requirement Rate

Contrary to the limitation of OEE, the proposed OEE can clearly shows that it is capable of identifying changes in customer demand through the new performance indicator, customer requirement rate, as demonstrated by the three-case numerical example. Also, OEE is improved by accounting for adjustments made in equipment loading time, as a result of manipulating planned downtime. This is why the new OEE is suggested for use by TPM-driven production responsible managers (Hubl et al., 2009). From the results of Case 2, it is seen that the drop of demand affects OEE negatively, prompting improvements for the process by adjusting shift times, as was done in Case 3. The new rate allows comparing the time used to actually produce high quality products that directly satisfy a customer order, and the adjustable loading time. Despite the importance of both original and proposed OEE metrics, it is up for company personnel to further investigate production losses and wastes with the help of OEE, to optimally steer TPM initiatives (Puvanasvaran et al., 2019). Production managers are advised to address each OEE indicator alone in order to facilitate the needed focus to eliminate specific process losses.

# 7 Conclusion

OEE is a significant performance measurement system for successful implementation of TPM activities. Despite its many benefits, the key figure OEE has received a lot of criticism both in literature and application. As such, this research explored the strengths, weaknesses, threats, and possible opportunities as to how to further develop or redesign this metric to overcome some of its limitations. It was clear from the conducted SWOT analysis that OEE arguably suffers from two main limitations: its inability to adequately visualize losses and inability to account for changes in market demanded products. Consequently, two new performance indicators, usability and customer requirement rate, were incorporated into the original OEE method to overcome its identified limitations. This research's findings are valuable as it provides production managers with a better understanding of OEE, and a more comprehensive tool acting as an extension to the maturity of OEE for successful implementation and use of this performance indicator. The new OEE measurement's value can mainly be attributed to its more meticulous categorization of losses, and its recognition of customer demand changes. These two additional characteristics of OEE contribute to its expansion and maturity as a TPM performance measurement system. However, it is still important to note that the proposed OEE is not without a flaw and actually several drawbacks of the original OEE will be also shared with the proposed one. This research aims to contribute to the OEE literature by offering a new improved OEE version which overcomes some of the limitations of the traditional method.

Despite the fact that conducting a case study with a real assembly line would have been ideal, this is seldom feasible (Huang et al., 2003). Usually, the costs associates with altering a system's design, parameters, and available resources in each process being analyzed are high due to financial constraints for realizing change and losses that take place due to process disruptions. Testing different scenarios with an existing real-life manufacturing process is impractical in most cases, because in reality most activities and disruptions take place in many different forms and degrees of magnitude. Even highly automated processes witness uncertainties and variability, and with the addition of labour resources, the potential for process variation increases even more. Hence, simulation, or in this case numerical examples, offers a unique opportunity to the researcher to attempt to model a system that represents a real production line using secondary data from previously conduced OEE case studies that provides approximations of the effects of process variations and disruptions that impede system performance (Huang et al., 2003). Nonetheless, further research should aim to improve the validity and reliability of the proposed OEE by applying it to real life case studies that use primary data, as opposed to secondary as done in this case. Moreover, future research efforts can explore OEE from more specialized perspectives using one of the scopes mentioned in the limitations section in the first chapter of this paper.

# 8 References

Ahuja, I. and Khamba, J., 2008. Total productive maintenance: literature review and directions. *International Journal of Quality and Reliability Management*, 25(7), pp.709-756.

Andersson, C. and Bellgran, M., 2015. On the complexity of using performance measures: Enhancing sustained production improvement capability by combining OEE and productivity. *Journal of Manufacturing Systems*, 35, pp.144-154.

Badiger, A. and Gandhinathan, R., 2008. A proposal: evaluation of OEE and impact of six big losses on equipment earning capacity. *International Journal of Process Management and Benchmarking*, 2(3), pp.234-248.

Bamber, C., Castka, P., Sharp, J. and Motara, Y., 2003. Cross☐functional team working for overall equipment effectiveness (OEE). *Journal of Quality in Maintenance Engineering*, 9(3), pp.223-238.

Benjamin, S., Marathamuthu, M. and Murugaiah, U., 2015. The use of 5-WHYs technique to eliminate OEE's speed loss in a manufacturing firm. Journal of Quality in Maintenance Engineering, 21(4), pp.419-435.

Binti Aminuddin, N., Garza-Reyes, J., Kumar, V., Antony, J. and Rocha-Lona, L., 2016. An analysis of managerial factors affecting the implementation and use of overall equipment effectiveness. *International Journal of Production Research*, 54(15), pp.4430-4447.

Cheah, C., Prakash, J. and Ong, K., 2020. An integrated OEE framework for structured productivity improvement in a semiconductor manufacturing facility. *International Journal of Productivity and Performance Management*, ahead-of-print (ahead-of-print).

Che Maideen, N., Budin, S., Sahudin, S. and Ab Samat, H., 2017. Synthesizing the Machine's Availability in Overall Equipment Effectiveness (OEE). *Journal of Mechanical Engineering*, 4(3), pp.89-99.

Dal, B., Tugwell, P. and Greatbanks, R., 2000. Overall equipment effectiveness as a measure of operational improvement – A practical analysis. *International Journal of Operations Production Management*, 20(12), pp.1488-1502.

De Ron, A. and Rooda, J., 2006. OEE and equipment effectiveness: an evaluation. *International Journal of Production Research*, 44(23), pp.4987-5003.

Domingo, R. and Aguado, S., 2015. Overall Environmental Equipment Effectiveness as a Metric of a Lean and Green Manufacturing System. *Sustainability*, 7(7), pp.9031-9047.

Fekri Sari, M. and Avakh Darestani, S., 2019. Fuzzy overall equipment effectiveness and line performance measurement using artificial neural network. *Journal of Quality in Maintenance Engineering*, 25(2), pp.340-354.

Ferko, R. and Znidarsic, A., 2007. Using OEE Approach for improving manufacturing performance. *Journal of Microelectronics, Electronic Components*, and Materials, pp.105-111.

Garza Reyes, J., 2015. From measuring overall equipment effectiveness (OEE) to overall resource effectiveness (ORE). *Journal of Quality in Maintenance Engineering*, 21(4), pp.506-527.

Garza Reyes, J., Eldridge, S., Barber, K. and Soriano Meier, H., 2010. Overall equipment effectiveness (OEE) and process capability (PC) measures: A relationship analysis. *International Journal of Quality  Reliability Management*, 27(1), pp.48-62.

Gibbons, P. and Burgess, S., 2010. Introducing OEE as a measure of lean Six Sigma capability. *International Journal of Lean Six Sigma*, [online] 1(2), pp.134-156.

Globerson, S., 1985. Issues in developing a performance criteria system for an organization. *International Journal of Production Research*, 23(4), pp.639-646.

Gupta, A. and Garg, R., 2012. OEE Improvement by TPM Implementation: A Case Study. *International Journal of Engineering and Applied Sciences Research (IJIEASR)*, 1(1), pp.115-124.

Gupta, P. and Vardhan, S., 2016. Optimizing OEE, productivity and production cost for improving sales volume in an automobile industry through TPM: a case study. *International Journal of Production Research*, 54(10), pp.2976-2988.

Hedman, R., Subramaniyan, M. and Almstrom, P., 2016. Analysis of Critical Factors for Automatic Measurement of OEE. In: *49th CIRP Conference on Manufacturing Systems*. Elsevier B.V., pp.128-133.

Huang, S., Dismukes, J., Shi, J., Su, Q., Razzak, M., Bodhale, R. and Robinson, D., 2003. Manufacturing productivity improvement using effectiveness metrics and simulation analysis. *International Journal of Production Research*, 41(3), pp.513-527.

Hubl, A. and Gmainer, R., 2008. Critical discussion of OEE.

Hubl, A., Altendorfer, K., Pilstl, J. and Jodlbauer, H., 2009. Equipment Performance Measurement in Production Plants Based on Customer Demand. In: *2009 2nd International Symposium on Logistics and Industrial Informatics*. Steyr: Institute of Electrical and Electronics Engineers.

Jeong, K. and Phillips, D., 2001. Operational efficiency and effectiveness measurement. *International Journal of Operations Production Management*, 21(11), pp.1404-1416.

Jonsson, P. and Lesshammar, M., 1999. Evaluation and improvement of manufacturing performance measurement systems □ the role of OEE. *International Journal of Operations and Production Management*, [online] 19(1), pp.55-78.

Kumar, J. and Soni, V., 2014. An Exploratory Study of OEE Implementation in Indian Manufacturing Companies. *Journal of The Institution of Engineers (India): Series C*, 96(2), pp.205-214.

Kumar, J., Sujatha, G. and Thyagarajan, D., 2012. Assessment of overall equipment effectiveness, efficiency and energy consumption of breakfast cereal. *International Journal of Applied Engineering and Technology*, 2(2), pp.39-48.

Kwon, O. and Lee, H., 2004. Calculation methodology for contributive managerial effect by OEE as a result of TPM activities. *Journal of Quality in Maintenance Engineering*, 10(4), pp.263-272.

Ljungberg, Õ., 1998. Measurement of overall equipment effectiveness as a basis for TPM activities. *International Journal of Operations Production Management*, 18(5), pp.495-507.

Lkiya, L. and Kushwaha, D., 2015. OPTIMIZING and ANALYZING OVERALL EQUIPMENT EFFECTIVENESS THROUGH TPM APPROACH: A CASE STUDY IN CEMENT INDUSTRY. *International Journal of Advance Engineering and Research Development*, 2(05).

Mahmoud, K., Otto, T., Shevtshenko, E. and Karaulova, T., 2016. Performance Evaluation By Using Overall Equipment Effectiveness (OEE): An Analyzing tool. In: *International Conference on Innovative Technologies*, IN-TECH 2016, Prague, 6. - 8. 9. 2016. [online]

Tallinn, pp.185-188.

Mansor, M., Ismail, A., Yasin, M. and Halim, A., 2015. A Framework for Measuring The Effect of Changeover Time To Overall Equipment Effectiveness. *University Malaysia Pahang 2015*.

Mishra, R., Anand, G. and Kodali, R., 2008. A SWOT analysis of total productive maintenance frameworks. *International Journal of Management Practice*, 3(1), p.51.

Muchiri, P. and Pintelon, L., 2008. Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. *International Journal of Production Research*, [online] 46(13), pp.3517-3535.

Nakajima, S., 1989. Implementing Total Productive Maintenance. Portland: Productive Press.

Ng, K., Chong, K. and Goh, G., 2014. Improving Overall Equipment Effectiveness (OEE) through the six sigma methodology in a semiconductor firm: A case study. In: *2014 IEEE International Conference on Industrial Engineering and Engineering Management*. [online] Melaka: Institute of Electrical and Electronics Engineers, pp.833-837.

Oechsner, R., Pfeffer, M., Pfitzner, L., Binder, H., Müller, E. and Vonderstrass, T., 2002. From overall equipment efficiency (OEE) to overall Fab effectiveness (OFE). *Materials Science in Semiconductor Processing*, 5(4-5), pp.333-339.

Olhager, J., Prajogo, D., Sohal, A. and O'neill, P., 2010. Implementation of OEE – issues and challenges.

Puvanasvaran, A., Yoong, S. and Tay, C., 2019. NEW OVERALL EQUIPMENT EFFECTIVENESS FRAMEWORK DEVELOPMENT WITH INTEGRATION OF MAYNARD OPERATION SEQUENCE TECHNIQUE. *Journal of Engineering and Applied Science*, 14(20), pp.3600-3608.

Puvanasvaran, P., Y.S., T. and C.C., T., 2013. Consideration of demand rate in overall equipment effetiveness (OE) on equipment with constant process time. *Journal of Industrial Engineering and Management*, 6(2), pp.507-524.

Roessler, M. and Abele, E., 2013. Uncertainty in the analysis of the overall equipment effectiveness on the shop floor. In: *IOP Conference Series: Materials Science and Engineering 46*. IOP Publishing Ltd.

Roessler, M. and Abele, E., 2015. Enhancement of the overall equipment effectiveness measure: a contribution for handling uncertainty in shop floor optimisation and production planning. *International Journal of Industrial and Systems Engineering*, 20(2), pp.141-154.

Sahu, S., Patidar, L. and Soni, P., 2015. 5S TRANSFUSION TO OVERALL EQUIPMENT EFFECTIVENESS (OEE) FOR ENHANCING MANUFACTURING PRODUCTIVITY. *International Research Journal of Engineering and Technology* (IRJET), 2(7), pp.1211-1216.

Sajid, M., Wasim, A., Hussain, S. and Jahanzaib, M., 2018. A Framework for Improving Overall Equipment Efficiency: A Case Study of Manufacturing Setup of Pakistan. *International Journal of Lean Thinking*, 9(2).

Shakil, S. and Parvez, M., 2020. Application of Value Stream Mapping (VSM) in a Sewing Line for Improving Overall Equipment Effectiveness (OEE): A Case Study. In: *Proceedings of ICIMES 2019: Intelligent Manufacturing and Energy Sustainability*, pp.249-260.

Singh, R., Shah, D., Gohil, A. and Shah, M., 2013. Overall Equipment Effectiveness (OEE) Calculation: Automation through Hardware Software Development. *Procedia Engineering*, 51, pp.579-584.

Sivaselvam, E. and Gajendran, S., 2014. Improvement of Overall Equipment Effectiveness In a Plastic Injection Moulding Industry. Journal of Mechanical and Civil Engineering, pp.12-16.

Wudhikarn, R., Smithikul, C. and Manopiniwes, W., 2010. Developing overall equipment cost loss indicator. In: *6th International Conference of Digital Enterprise Technology*. [online] Hong Kong. Available at: <http://10.1007/978-3-642-10430-543> [Accessed 15 March 2020].

Yalagi, S., A R, D. and Naik, C., 2016. Overall Equipment Effectiveness. *International Journal of Engineering Research And Advanced Technology*, 2(1), pp.521-528.

Ylipää, T., Skoogh, A., Bokrantz, J. and Gopalakrishnan, M., 2017. Identification of maintenance improvement potential using OEE assessment. *International Journal of Productivity and Performance Management*, 66(1), pp.126-143.

Zammori, F., Braglia, M. and Frosolini, M., 2011. Stochastic overall equipment effectiveness. *International Journal of Production Research*, 49(21), pp.6469-6490.

# 9 Appendix

## 9.1 Appendix 1: Experimental Setup in MS-Excel

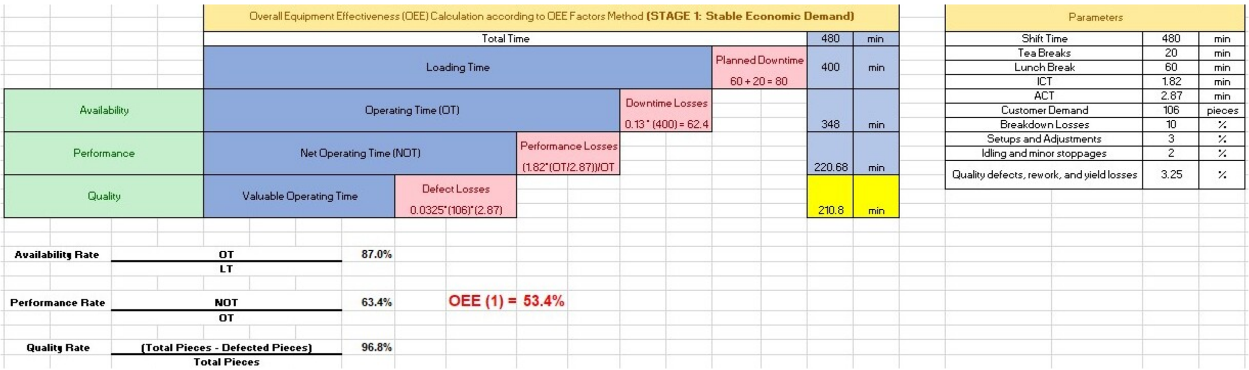



Figure 7: Experimental Setup: Original OEE Stage 1

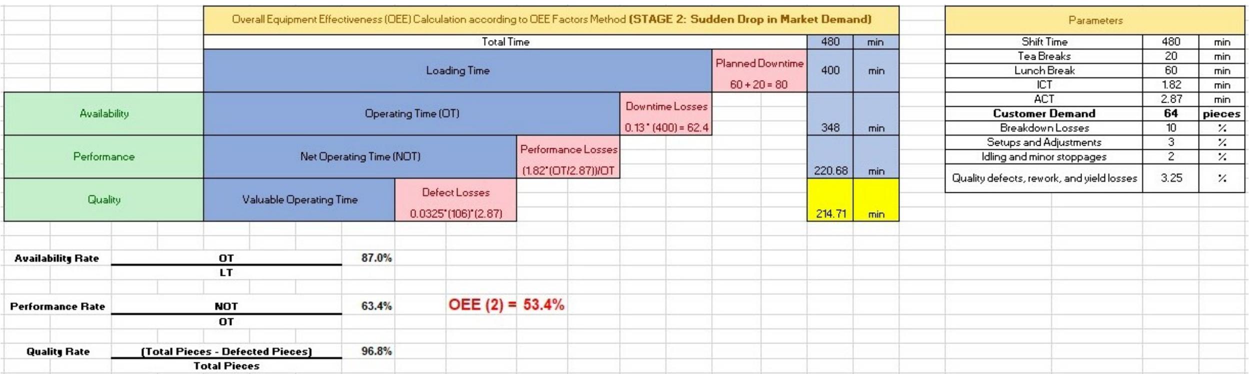



Figure 8: Experimental Setup: Original OEE Stage 2

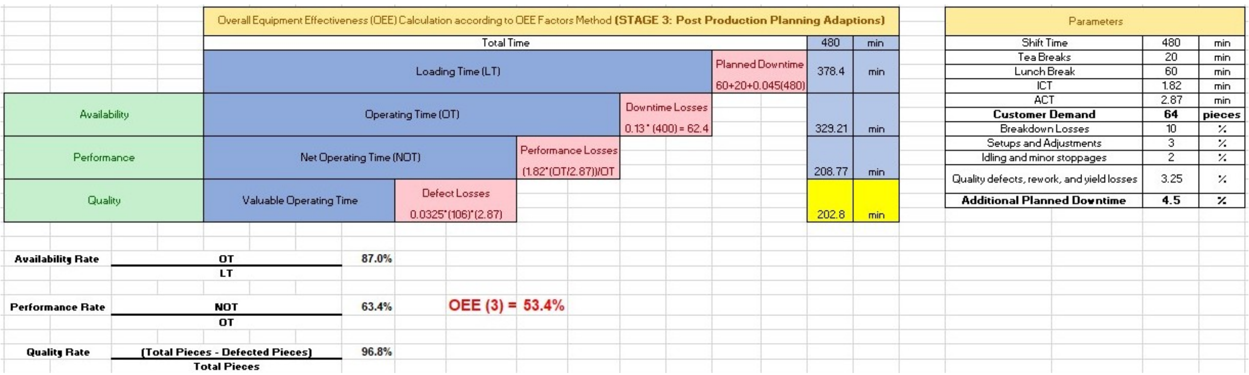



Figure 9: Experimental Setup: Original OEE Stage 3

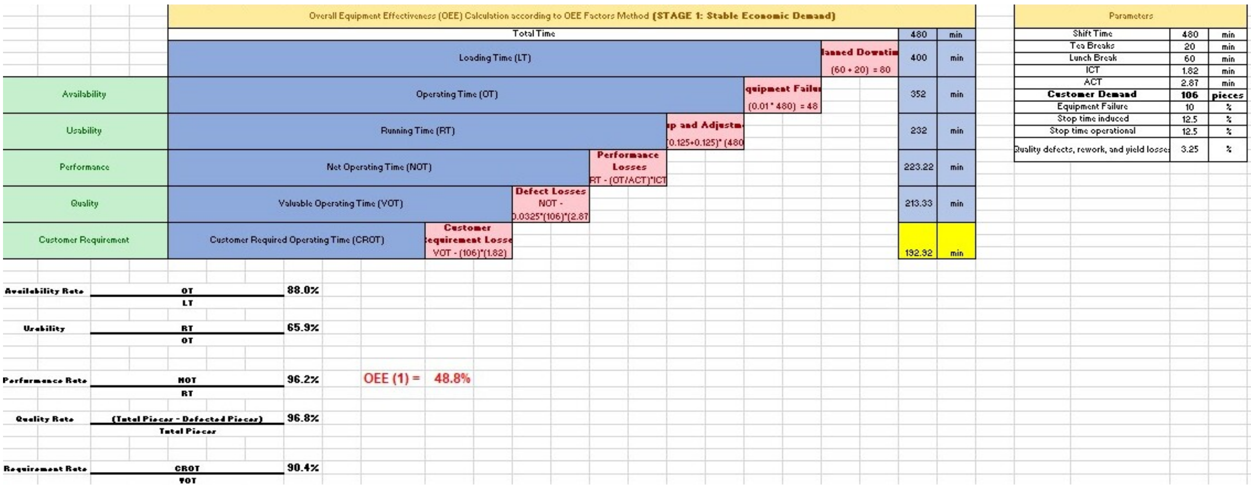



Figure 10: Experimental Setup: Proposed OEE Stage 1

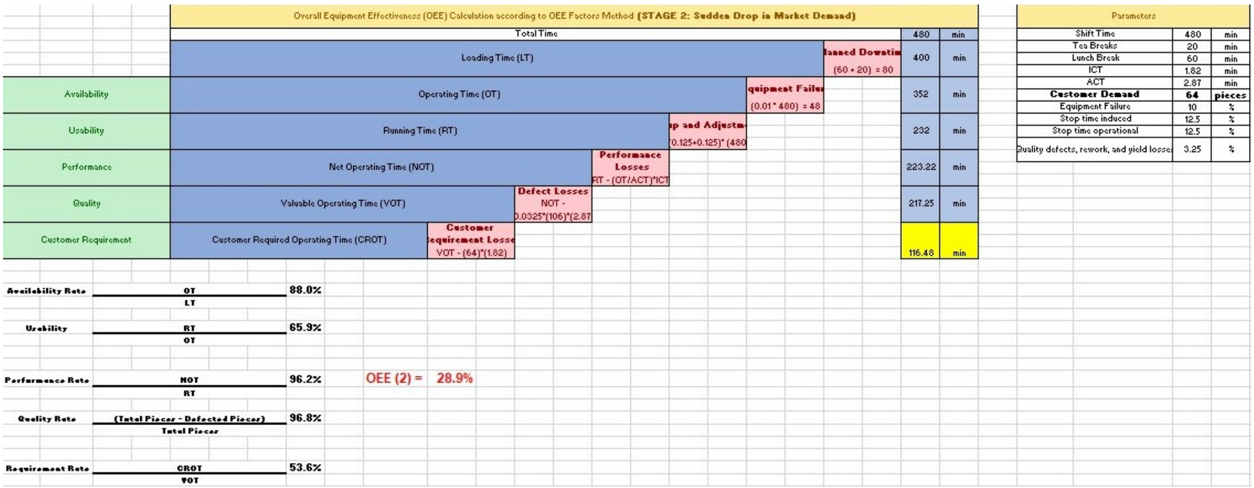



Figure 11: Experimental Setup: Proposed OEE Stage 2

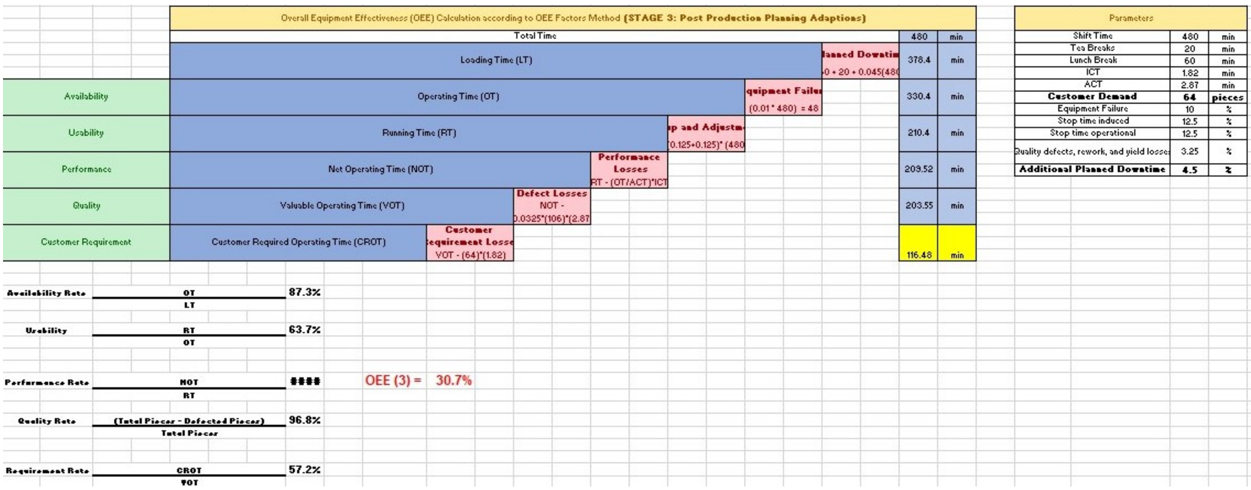



Figure 12: Experimental Setup: Proposed OEE Stage 3

## 9.2 Appendix 2: Original OEE Elements Results

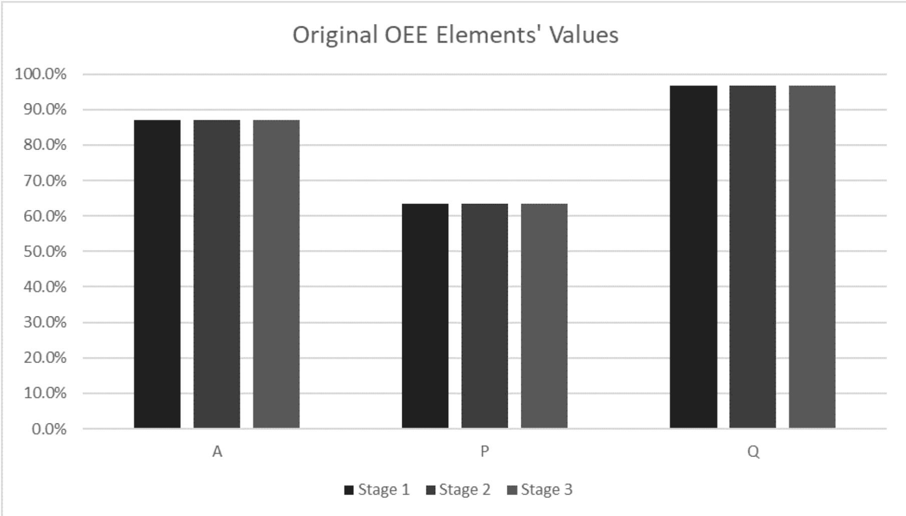



Figure 13: Original OEE Elements Cluster Chart

## 9.3 Appendix 3: Proposed OEE Elements Results

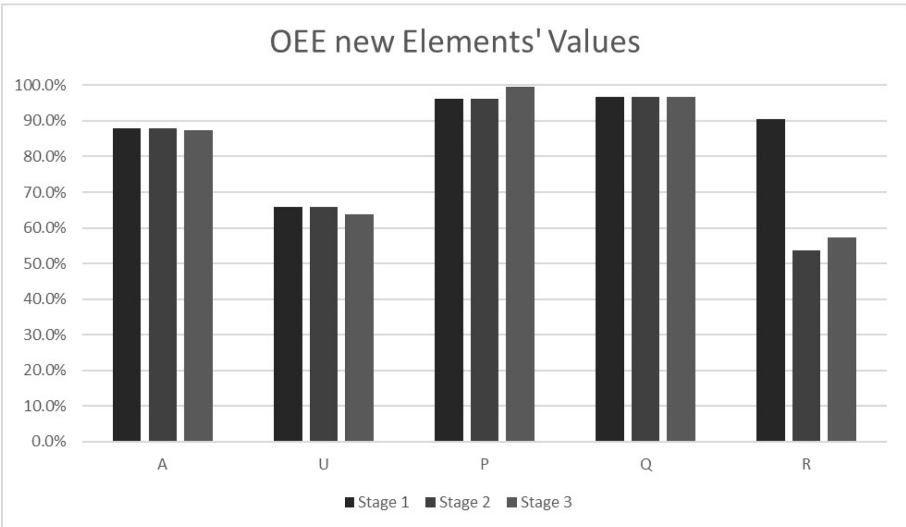



Figure 14: Proposed OEE Elements Cluster Chart

## 9.4 Appendix 4: Final OEE Results

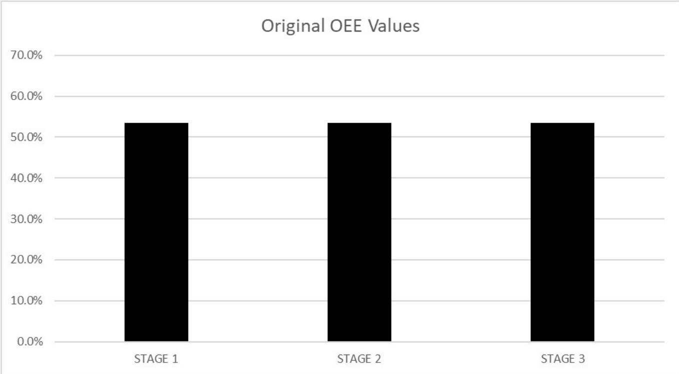



Figure 15: Original OEE Values Bar Chart

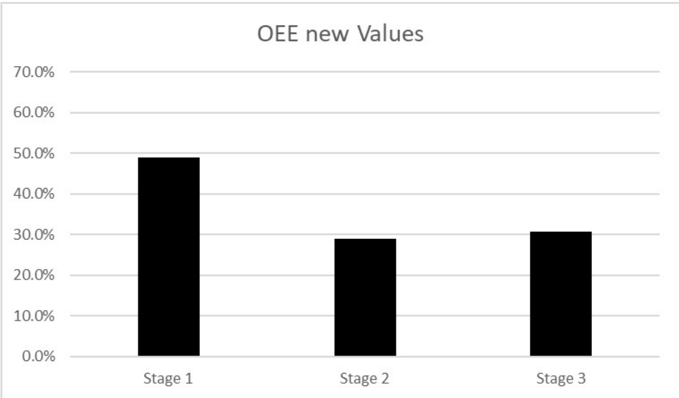



Figure 16: Proposed OEE Values Bar Chart