COMPARISON OF OEE-BASED MANUFACTURING PRODUCTIVITY METRICS

Bálint Árpád Ádám¹, Zoltán Sebestyén¹
¹ Budapest University of Technology and Economics, Budapest, Hungary

Abstract

Overall Equipment Effectiveness (OEE) is a widely used productivity metric for different pieces of equipment. It provides information on the effectiveness of production, so the percentage of valuable operation time to planned uptime of the machine. The OEE, as the core metric of Total Productive Maintenance (TPM), helps to identify losses in production and quantify operational efficiency allowing actions to be taken that contribute to the continuous improvement of the plant. Despite or perhaps due to its popularity, OEE is not an accurate, well-defined measure. This is because the same considerations cannot be used equally well in different industries or may serve different purposes from one company to another, causing modifications in the calculation and measurement methods. Therefore, the OEE concept may mean other things from company to company, industry to industry. Researchers have tried identifying and overcoming the drawbacks of the original OEE by defining new calculations and creating new metrics. This study aims to overview the indicators available in the literature and compare their advantages/disadvantages. It also seeks to clarify these different definitions, naming conventions, calculation methods, and investigate their usability and the limitations of applicability.

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1. Introduction

Measuring production efficiency is widespread in all fields of industry, as it can be used to detect various errors and identify hidden capacities. This benefit allows the latent capacities to be exploited, and productivity can be increased without any investment. In addition, increasing efficiency is critical due to today’s rising resource prices and energy reduction directives. For this reason, we dare to suppose, there is no production manager today who does not prioritise production efficiency. The authors of this article attempt to characterise and compare measures of production efficiency developed in recent decades from the original Overall Equipment Effectiveness (OEE) concept to nowadays’ metrics. This study aims to explore the advantages and disadvantages of measures and clarify definitions that are often used inconsistently.

2. Basic OEE calculation

The OEE calculation was originally proposed by Nakajima [1] as one of the main key performance indicators (KPI) for Total Productive Maintenance (TPM). The OEE measurement aims to detect production losses and maximise equipment effectiveness. The production-related losses, often mentioned as "six big losses", are the following:

Downtime:
- Equipment failure
- Setup and adjustment

Speed losses:
As defined by Nakajima, the OEE is derived from the multiplication of three sub-KPIs (Key Performance Indicator), which focus on the three different types of losses:

\[ OEE = \text{Availability} \cdot \text{Performance efficiency} \cdot \text{Rate of quality} \]

The availability refers to the rate of operation time to loading time:

\[ \text{Availability} = \frac{\text{Operation time}}{\text{Loading time}} \]

Due to the purpose of the OEE, the time baseline is not the total available time (e.g., usually one month or one year), but the loading time of the equipment. The loading time does not include scheduled downtimes due to the production plan, as this does not contribute to the operational efficiency of the equipment. Thus, capacity utilisation and traditional capacity indexes are not considered in the OEE calculation. The loading time – so the baseline of the calculation – can be calculated by subtracting the planned downtime from the total available time:

\[ \text{Loading time} = \text{Total available time} - \text{Planned downtime} \]

The planned downtime includes the planned maintenance time, bank holidays, and the pre-scheduled downtime in the production plan. Operation time counts the exact amount of time when the given equipment is running. Therefore, the loading time can be divided into operation time and equipment downtime, such as breakdown, and setup/adjustment time.

The second component of the OEE is performance efficiency which is the product of the operating speed rate and the net operating rate.

\[ \text{Performance efficiency} = \text{Operating speed rate} \cdot \text{Net operating rate} \]

The operating speed rate refers to the production speed losses. It indicates the differences between the actual and ideal speed or cycle time:

\[ \text{Operating speed rate} = \frac{\text{Ideal cycle time}}{\text{Actual cycle time}} \]

The net operating rate takes the minor stoppages into account. The value shows how stable the production is, so it is a comparison between the actual processing time and operation time:

\[ \text{Net operating rate} = \frac{\text{Processed amount} \cdot \text{Actual cycle time}}{\text{Operation time}} \]

The performance efficiency, as the product of operating speed rate and net operating rate, is the ratio between the ideal time required to produce the given amount and the operation time of the machine. Therefore, it indicates slowdowns compared to the ideal speed and minor stoppages during production:

\[ \text{Performance efficiency} = \frac{\text{Processed amount} \cdot \text{Ideal cycle time}}{\text{Operation time}} \]

The rate of quality reflects to the defects, as the time spent producing scrap is wasted time:

\[ \text{Rate of quality} = \frac{\text{Processed amount} - \text{Defect amount}}{\text{Processed amount}} = \frac{\text{Processed good amount}}{\text{Processed amount}} \]
After performing the multiplication, the OEE can be calculated as follows:

\[
OEE = \frac{\text{Processed good amount} \cdot \text{Ideal cycle time}}{\text{Loading time}}
\]

It shows how much time would be needed to produce the actually manufactured qualified amount of product under optimal conditions compared to the loading time of the machine. The relations of the OEE defined by Nakajima, the six big losses and the 3 sub-KPIs are summarised in Figure 1.

![Fig. 1. Overall Equipment effectiveness defined by Nakajima](image)

### 3. New KPIs based on OEE calculation

The OEE calculation has evolved significantly in the last three decades, leading to new indicators. The reasons for the improvements are manifold. The following section summarises the new measures based on the OEE, investigates the reasons behind the development, and analyses the advantages/disadvantages.

Ames et al. [2] interpreted the OEE calculation for semiconductor manufacturing equipment and defined SEMATECH’s approach to Overall Equipment Effectiveness. The main difference from the original concept is that the availability and, therefore, the OEE take the nonscheduled time (e.g., holidays, shutdown) into account. Due to this modification, the time basis of the calculation is the total time instead of the loading time. This change can be particularly beneficial for measuring high-value machines’ efficiency, where the nonscheduled periods should be avoided because of the cost of unused capacity. However, this calculation method can be misleading for intermittent or seasonal production, setting unachievable and meaningless goals.

Total Effectiveness Equipment Performance (TEEP) measures the equipment’s effectiveness relative to the total time, similar to Ames’s OEE calculation. The TEEP calculation also includes another factor, which is utilisation [3]:

\[
TEEP = \text{Utilization} \cdot OEE
\]

where

\[
\text{Utilization} = \frac{\text{Loading time}}{\text{Total time}}
\]

So, TEEP indicates the scheduling losses in production as well and is useful for the same cases as Ames’s OEE if the production runs 24/7.
The concept of Production Equipment Effectiveness (PEE) [4] for discrete-type production operations is similar to the original OEE by Nakajima. Accordingly, the same three sub-KPIs are included but allow weighting of the individual components. The significant parameters are given a higher weight so that PEE better reflects the critical losses, which are more important for the plant. The calculation method is as follows:

$$PEE = A^{k_1} \cdot p^{k_2} \cdot Q^{k_3}$$

The authors suggest using the analytical hierarchy process (AHP) to determine the appropriate weighting factors.

In the case of continuous process operations, the PEE is a function of availability, attainment, performance efficiency, quality rates, product support efficiency, and operating utility:

$$PEE = A_1^{k_1} \cdot A_2^{k_2} \cdot p^{k_3} \cdot Q^{k_4} \cdot PSE^{k_5} \cdot OU^{k_6}$$

The $A_1$ availability refers to the scheduled downtime and $A_2$ attainment reflects the unscheduled downtime. Thus, $A_1$ and $A_2$ can be seen as sub-categories of the OEE’s availability ($A$). With this separation, the two indicators can be given different weights. PSE and OU take account of transaction losses and no demand time; however, these can also be calculated as downtimes.

The OEE, despite its name, not only reveals the losses related to the equipment, but also considers the malfunctions and shortages in the environment of the equipment. Losses include not only failures or slowdowns caused by the equipment, but also stoppages and speed losses due to shortages of raw material and workforce, which concerns the organisation of production rather than the equipment itself. This feature was criticised by de Ron and Rooda [5], and they created a new metric, Equipment Effectiveness (E), which focuses solely on the equipment. The authors distinguished equipment-dependent and equipment-independent statuses and defined the effective time, which means when the equipment was able to perform its dedicated production task. The effective time excludes the equipment-independent causes and the duration of this status. The base of the Equipment Effectiveness (E) is the effective time. Thus, this KPI excludes production losses that cannot be closely linked to the operation of the equipment, which can be both an advantage and a disadvantage. On the one hand, it can be an advantage, e.g., the maintenance team, who are only concerned with the breakdowns and settings of the equipment. However, for coordinators, whose job is to manage the whole production, this KPI can mask severe errors, which is disadvantageous.

Hung et al. [3] defined new OEE-based KPIs, the value-added OEE and value-added TEEP (VAOEE and VATEEP). Common to both metrics, the original ones are multiplied by a design factor, which describes the design cycle. The production cycle can be divided into value-added and non-value-added sub-processes, and the ratio of the value-added steps to the whole cycle is the design factor:

$$Design = \frac{Value\text{-}added\text{time\ in\ a\ design\ cycle}}{Design\ cycle\ time}$$

Thus, the VAOEE can be calculated as follows:

$$VAOEE = OEE \cdot Design = \frac{Processed\ good\ amount \cdot (Value\text{-}added\text{time\ in\ a\ design\ cycle})}{Loading\ time}$$

The authors questioned the assumption that the design cycle is the shortest possible time. If this approximation is not met, the OEE-based developments have limitations, and hidden capacities remain in production despite the maximised OEE. Nevertheless, process optimisation cannot significantly impact production efficiency if the original OEE-related losses are enormous. Alternatively, in some fields of industry, due to the nature of manufacturing, it is difficult to bypass or omit some non-value-added but necessary steps.

Some KPIs derived from OEE target not only operational efficiency but also include financial implications. The Overall Resource Effectiveness (ORE) broadens the scope of OEE with the value of resources [6]. ORE is the ratio of recovered investment (output) to the overall investment (input).
The inputs are split into two groups, namely the material and resource inputs required to run the process. Both types of inputs have an efficiency parameter: the first one is material efficiency, and the second one is the OEE. Material efficiency evaluates how efficiently the raw materials are transformed, while the OEE, in this interpretation, measures how efficiently the production-related resources are used. The ORE combines these two aspects of the production and can be calculated with the following expression:

\[ ORE = \frac{OEE \cdot PIMV + M \cdot MIMV}{PIMV + MIMV} \]

Where the process input monitoring value (PIMV) and the material input monitoring value (MIMV) represent the economic investment in materials and resources to sustain a process. The ORE focuses not only on production effectiveness, but also on the value of the components involved in manufacturing, making it both an operational and financial KPI.

Wudhikarn et al. [7] argued that the OEE is unsuitable for benchmarking and prioritising because it neglects the different capacities of the machines, the production cost, and the product’s value. Without these considerations, the focus can be inappropriate, as the impact of operational losses in the money dimension is not equal for different pieces of equipment. The OECL calculation considers the opportunity cost and the production cost as well. With OECL, production inefficiencies can be translated into cost, making it more transparent for financial managers. This approach was further developed by combining it with the cost of quality, resulting in the Overall Equipment Quality Cost Loss (OEQCL) [8].

Several authors have extended the understanding of the OEE from the machine level to the manufacturing line level or even to the whole plant, factory level. In general, machines are not independent of each other, and are not stand-alone pieces of equipment. The previous or next machine often influences the given machine in the manufacturing line. Therefore, it is more suitable to measure the effectiveness of the whole line instead of calculating the individual machines’ OEE one by one. It is possible with the concept of Overall Line Effectiveness (OLE) [9]. In this KPI, the availability is replaced by the line availability (LA) and the performance efficiency is merged with the rate of quality resulting in the line production quality performance efficiency (LPQP):

\[ OLE = LA \cdot LPQP \]

The line availability is calculated from the \( n \)th (last) machine’s operating time and the planned line loading time. While the \( LPQP \) can be obtained from the processed good amount by the \( n \)th machine \((G_n)\), the cycle time of the bottleneck machine (which is the largest cycle time) \((CYT_{bn})\) and the operating time of the 1st machine \((OT_1)\):

\[ LPQP = \frac{G_n \cdot CYT_{bn}}{OT_1} \]

The equation can be used to calculate the line effectiveness. However, it has to be highlighted that this relation is only applicable in that case, when the machines are connected in series, the line is continuous (no buffers), and the operating time of the previous equipment is the loading time of the following equipment in the series.

Braglia et al. [10] criticised the OLE metric as it only focuses on the last machine in the manufacturing line, making it hard to recognise where the main criticalities occur. They proposed a new metric, namely the Overall Equipment Effectiveness of a Manufacturing Line (OEEM). The OEEM can be calculated from the good amount processed by the \( n \)th machine, the bottleneck cycle time \((CYT_{bn})\) and the line loading time \((LLT)\):

\[ OEEM = \frac{G_n \cdot LLT}{CYT_{bn}} \]

Scott and Pisa [11] proposed the Overall Factory Effectiveness (OFE), which is a factory-level OEE-based KPI. They did not publish a well-defined metric to measure plant efficiency, considering that different companies and factories have other goals [12]. So, they proposed that the firms build their own
OFE measures by combining metrics that are important for them. These KPIs can be, for example, the OEE, capacity utilisation, yield, and ramp-up performance.

One possible OFE metric was announced by Huang et al. [13], the Overall Throughput Effectiveness (OTE). The OTE can be calculated on a given time period as

\[
OTE = \frac{\text{Good product output from factory}}{\text{Theoretical attainable product output from factory in total time}}
\]

The OTE can be determined for different types of sub-systems, such as machines in series or parallel. Then, the OTE for the sub-systems can be used to calculate the OFE level indicator.

4. Conclusion

The advantages and disadvantages of the above metrics are discussed below. More precisely, it is impossible to present pro-contra properties since the same feature of a given efficiency indicator is advantageous in some cases and disadvantageous in other applications. Therefore, discussing industrial applications rather than benefits and drawbacks is more beneficial.

Table 1. shows the KPIs presented in the article, grouped into five categories based on how the original OEE was modified. The main features are also summarised in the table.

<table>
<thead>
<tr>
<th>Modification of OEE</th>
<th>KPIs</th>
<th>Main feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reallocate/extend the production-related time</td>
<td>Ames’s OEE TEEP E VAOEE/VATEEP</td>
<td>Utilisation is part of the calculation Omits the non-machinery losses Considers the value-added/non-value-added steps</td>
</tr>
<tr>
<td>Weighting components</td>
<td>PEE ORE OECL OEQCL</td>
<td>Allows weighting Value of resources is part of the calculation Calculates with the opportunity cost and production cost loss OECL extended with the cost of quality</td>
</tr>
<tr>
<td>Considering financial aspects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extending to line level</td>
<td>OLE OEEML</td>
<td>Shows the efficiency of the production line without buffers Shows the efficiency of production lines with buffers</td>
</tr>
<tr>
<td>Extending to plant level</td>
<td>OFE OTE</td>
<td>Product of different KPIs It is calculated from the production sub-systems of the factory</td>
</tr>
</tbody>
</table>

These key properties determine the usability of each metric. They can be used to decide which indicator is appropriate considering the production parameters.

Ames’s OEE and the TEEP are technically the same. The baseline of the calculation is the total time. Using total time as baseline is advantageous when the production is 24/7 or if the machine is high-value, highly automated. In this case, the cost of unused capacity would be very high if there were much unscheduled time on the machine.

The Equipment Effectiveness (E) focuses solely on the machine and not on external factors affecting it, as it excludes the machine-independent losses from the calculation. It can be useful for the maintenance department of the firm, but not for production managers.
VAOEE and VATEEP allow a higher resolution by also analysing the cycle time that is considered ideal. These metrics can be helpful when the original OEE can no longer be realistically improved. In some industries, such as pharmaceuticals, where there are many processing and purification steps in addition to a main process, it is impossible to leave out the necessary but non-value-added steps. Consequently, VAOEE/VATEEP cannot be raised above a certain level.

PEE allows the inherent OEE components to be weighted resulting in a measure that focuses more/less on different problems. It is advisable to use it when, for example, there is a known high-impact loss to which the plant wants to pay more attention.

ORE, OECL, OEQCL consider financial aspects as well. The ORE calculates with the value of the resources, which allows e.g. scrap or rework to be expressed in monetary dimension rather than just in time. It is thus possible to show that the same time losses have different financial impacts depending on the product’s value. OECL can also show opportunity costs and production cost losses. The OEQCL is further extended with the cost of quality. With these changes, the OEE production indicator has become a financial KPI, which can be a valuable indicator for strategic decisions and the financial department of the company.

OLE and OEEML are production line-level indicators. While OLE does not, OEEML allows the use of buffers between machines. These indicators measure the performance of the whole line. This is particularly useful where machines are highly interdependent, where it makes no sense or is not even possible to describe the performance of just one single piece of equipment.

In addition, OFE is an even higher-level metric, as it can describe the factory performance. It is a product of different KPIs and less well-defined than the KPIs discussed so far. On the one hand, it is advantageous that each company can define its own plant-level indicator. However, it is not suitable for benchmarking between companies. A well-defined OFE metric is the OTE. The OTE can be used to describe the efficiency of each sub-system, which can be summed to obtain the efficiency of the factory; although, the calculation for large systems can be complex. Another disadvantage of higher-level indicators is that the more information they are composed of, the more difficult it is to see the actual content.

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References


