OEE and equipment effectiveness E: an evaluation

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OEE and equipment effectiveness: an evaluation

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Abstract

Overall equipment effectiveness or efficiency *OEE* is a metric that has been accepted completely in the semiconductor industry. *OEE* is simple and clear, and standards and guidelines have been developed. Nonetheless literature indicates imperfections in applying *OEE* with regard to time base and rate efficiency. As *OEE* lacks a proper framework, equipment effectiveness *E* has been developed based on a systematic approach of the equipment. *E* considers the effectiveness of equipment with respect to availability, speed and quality losses. Unlike *OEE*, *E* is a performance measure for stand-alone equipment, isolated from the environment. In addition, *E* uses the available effective time as base in contrast to *OEE* that uses the total time as a base for measurement. Finally, due to the fact that *E* is directly measured by production and effective time, it does not depend on the utilization of the equipment, unlike *OEE*. Furthermore, it has been shown that *OEE* does not indicate the influence of down time and rework, while *E* shows these influences in a right way.

1 Introduction

Performance measurement is a topic that is often discussed in literature. Performance can be defined as to what extend the state of a company or of the processes fulfil the objectives. Measuring the performance of processes gives information about the status of the processes and enables to make decisions about adjustments of settings or about improvement actions. Kaydos [1] defines five major reasons for companies to measure performance:

- Improved control, since feedback is essential for any system.
- Clear responsibilities and objectives because good performance measures clarify who is responsible for specific results or problems.
- Strategic alignment of objectives because performance measures have proven to be a good means of communication for company's strategy throughout an organization.
- Understanding business processes since measuring data requires understanding of the manufacturing processes.
- Determining process capability because understanding a process also means knowing its capacity.

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A key performance measure in mass-production environments is Overall Equipment Effectiveness *OEE*. *OEE* has been introduced by Nakajima [2] within the context of Total Productivity Maintenance (TPM) and is directed to equipment/machines. As *OEE* is a simple and clear overall metric managers appreciate such an aggregated metric instead of many detailed metrics. Huang *et al.* [3] write that the concept of *OEE* is becoming increasingly popular and that it has been widely used as a quantitative tool essential for measurement of productivity in semiconductor manufacturing operations, because of an extreme capacity constrained facility investment. They state that traditional metrics for measuring productivity, throughput and utilization, are insufficient for identifying the problems and underlying improvements needed to increase productivity.

Semiconductor Equipment and Materials International (SEMI) has developed a standard for definition and measurement of *OEE* as introduced by [2]. The standard is directed to measuring the effectiveness of equipment. SEMI renamed the metric Overall Equipment Efficiency as it is expressed entirely in terms of time. The standard has been described in [4] and uses definitions as laid down in [5]. A guide to apply *OEE* is described in [6].

Previous research has targeted various aspects of *OEE*. For example, Ljunberg [7] states that the definition of *OEE* does not take into account all factors that reduce the capacity utilization, e.g. planned downtime, lack of material input, lack of labor. In addition, the available time would be a more appropriate basis for time measurement than the loading time as it was originally used by [2]. Similarly, De Groote [8] utilizes a fixed planned production time and calculates the difference between actual and planned production time. The need for a more appropriate time basis is supported by [9], [10] and [11]. It is generally observed that the accuracy of *OEE* is largely determined by the quality of the collected data.

The description given in [2] and [4] is directed to equipment, but it is noticed that *OEE* is impacted greatly by factors beyond the equipment itself, including operator, recipe, facilities, material (input items) availability, scheduling requirements, etc. As this impact may result in *OEE* values that show the influence of factors beyond the equipment instead of the equipment itself, a distinction can be made between stand-alone equipment and integrated equipment. *OEE* is directed to equipment integrated in a manufacturing environment so that *OEE* includes influences of this environment.

As it lacked a metric directed to stand-alone equipment, De Ron and Rooda [12] have proposed equipment effectiveness *E*. This performance measure has been derived to monitor the effectiveness of stand-alone equipment, independent from the environment.

The aim of this paper is to describe the behavior of *OEE* and *E* as performance measure for manufacturing equipment.

In Section 2 *OEE* is described shortly. In this Section, the influence of equipment utilization, down time and rework are discussed too. A description of equipment effectiveness *E* is given in Section 3 as well as a description of the influence of utilization, down time and rework. A comparison between the performance measures is described in Section 4, while the conclusions are presented in Section 5.

2 Overall Equipment Effectiveness *OEE*

In considering *OEE*, Nakajima [2] defines six big equipment losses:

1. Equipment failure/breakdown losses are categorized as time losses when productivity is reduced, and quality losses caused by defective products,
2. Set-up/adjustment time losses result from downtime and defective products that occur when production of one item ends and the equipment is adjusted to meet the requirements of another item,
3. Idling and minor stop losses occur when the production is interrupted by a temporary malfunction or when a machine is idling,
4. Reduced speed losses refer to the difference between equipment design speed and actual operating speed,
5. Reduced yield occurs during the early stage of production from machine start up stabilization,
6. Quality defects and rework are losses in quality caused by malfunctioning production equipment.

The first two losses are known as downtime losses and are used to calculate availability V of a machine. The third and fourth losses are speed losses that determine the so-called performance efficiency P of a machine, i.e. the losses which occur as a consequence operating at less than the optimum conditions. The final two losses are considered to be losses due to defects, the larger the number of defects the lower quality rate Q of parts within the factory. Then, OEE is measured by:

$$OEE = V \cdot P \cdot Q$$

with:

$$V = \frac{\text{loading time} - \text{downtime}}{\text{loading time}}$$

$$P = \frac{\text{theoretical cycle time} \times \text{processed amount}}{\text{operating time}}$$

$$Q = \frac{\text{processed amount} - \text{defect amount}}{\text{processed amount}}$$

Loading time is working time minus planned downtime, while downtime means stoppage time losses because of breakdowns, setup and adjustments.

SEMI [4] expresses OEE entirely in terms of time. In [5] six main states of manufacturing equipment are defined, see Figure 1. By using these states, the following definition of overall equipment efficiency OEE is given [4]:

$$OEE = \frac{\text{theoretical production time for effective units}}{\text{total time}}$$

Figure 1: OEE equipment states

OEE is built up by means of availability efficiency *AE*, operational efficiency *OE*, rate efficiency *RE* and quality efficiency *QE*:

$$OEE = AE \cdot (OE \cdot RE) \cdot QE \quad (1)$$

with:

$$AE = \frac{\text{equipment uptime}}{\text{total time}} \quad (2)$$

$$OE = \frac{\text{production time}}{\text{equipment uptime}} \quad (3)$$

$$RE = \frac{\text{theoretical production time for actual units}}{\text{production time}}$$

$$QE = \frac{\text{theoretical production time for effective units}}{\text{theoretical production time for actual units}}$$

In these definitions theoretical production time means production time at strictly theoretically efficient rates without efficiency losses.

In the next examples the application of *OEE* is illustrated.

	A	B
total time	168h	168h
non-scheduled time	0h	0h
standby time	72h	48h
production time	84h	105h
engineering time	0h	0h
total (un)scheduled down time	12h	15h
theoretical production time per unit	0.044h	0.044h
maximum throughput	22.73 /h	22.73 /h
number of items	1860	2324
number of qualified items	1810	2261

Table 1: Measurement data set I

	A		B	
<i>AE</i>	(168-12)/168	= 0.929	(168-15)/168	= 0.911
<i>OE</i>	84/(168-12)	= 0.538	105/(168-15)	= 0.686
<i>RE</i>	1860 · 0.044/84	= 0.974	2324 · 0.044/105	= 0.974
<i>QE</i>	1810/1860	= 0.973	2261/2324	= 0.973
<i>OEE</i>	0.929 · 0.538 · 0.974 · 0.973	= 0.474	0.911 · 0.686 · 0.974 · 0.973	= 0.592

Table 2: Results of *OEE* for data set I

Table 1 shows the measurement data for the two situations. The difference between both situations is that in case B the throughput is larger than in case A so that the productive time is larger and more items are produced. Because of the larger production time, the down time is increased and the standby time decreased as more capacity is required. The results are given in Table 2.

The results show that the *RE* and *QE* for both situations are the same. The differences are expressed by *AE* and *OE* and, as a consequence, by the *OEE* values. As the throughput is increased in case B, the differences between both measurements are not caused by the machine or workstation but by the environment of it.

The influence of the environment on *OEE* can be treated more generally by considering the utilization. This measure indicates the part of the total time that capacity of the machine is requested.

Equation (1) shows that *OEE* contains the product of *AE* and *OE*. This product can be expressed in terms of natural process time t_o (productive time/number of items) and inter-arrival time t_a (total time/number of items):

$$AE \cdot OE = \frac{\text{production time}}{\text{total time}} = \frac{t_o}{t_a} \tag{4}$$

For a particular manufacturing system, the product of *AE* and *OE* depends upon utilization u , which can be seen as follows:

$$AE \cdot OE = \frac{t_o}{t_a} = \frac{t_0}{t_e} \cdot \frac{t_e}{t_a} = A \cdot u \tag{5}$$

In this equation, it is used that availability A and utilization u can be written in terms of natural process time t_0 , effective process time t_e and arrival time t_a :

$$A = \frac{t_0}{t_e}$$
$$u = \frac{t_e}{t_a}$$

The effective process time is defined as the total amount of time an item exploits capacity from a system, until it is processed as a qualified lot [15].

By substituting equation (5) in (1) we obtain:

$$OEE = \frac{t_0}{t_a} \cdot RE \cdot QE = A \cdot RE \cdot QE \cdot u \tag{6}$$

The dependency of OEE upon utilization u is determined by the submetrics AE and OE . By using equation (2) and (3) these submetrics can be expressed by:

$$AE = \frac{t_0 + (1-u)t_a}{t_a} = 1 - (1-A) \cdot u \quad (7)$$

$$OE = \frac{t_0}{t_0 + (1-u)t_a} = \frac{u \cdot A}{1 - u \cdot (1-A)} = \frac{A}{AE} \cdot u \quad (8)$$

Remark that equation (8) shows that AE and OE are mutually dependent.

Figure 2 illustrates the dependence of OEE , AE and OE of utilization, see equation (6), (7) and (8).

Figure 2: Influence of u on OEE , AE and OE ($A=0.833$; $RE=1$; $QE=1$)

The dependence of OEE on utilization u is caused by the fact that OEE has not been defined by equipment parameters but by a mix of equipment parameters and exogenous variables.

A second example is directed to the influence of the down time, see Table 3. Case A is base situation as given also in Table 1. In Case C the downtime has doubled so that the standby time has been decreased.

	A	C
total time	168h	168h
non-scheduled time	0h	0h
standby time	72h	60h
production time	84h	84h
engineering time	0h	0h
total (un)scheduled down time	12h	24h
theoretical production time per unit	0.044h	0.044h
maximum throughput	22.73 /h	22.73 /h
number of items	1860	1860
number of qualified items	1810	1810

Table 3: Measured data set II

	A			C		
AE	$(168-12)/168 = 0.929$			$(168-24)/168 = 0.857$		
OE	$84/(168-12) = 0.538$			$84/(168-24) = 0.583$		
RE	$1860 \cdot 0.044/84 = 0.974$			$1860 \cdot 0.044/84 = 0.974$		
QE	$1810/1860 = 0.973$			$1810/1860 = 0.973$		
OEE	$0.929 \cdot 0.538 \cdot 0.974 \cdot 0.973 = 0.474$			$0.857 \cdot 0.583 \cdot 0.974 \cdot 0.973 = 0.474$		

Table 4: Results of OEE for data set II

The results are given in Table 4. Only the submetrics AE and OE are changed because of the increased downtime but their product has not changed as production time has not changed. As a consequence, OEE does not change in spite of the increased down time.

A last example concerns equipment with rework. In case of rework availability efficiency AE and operational efficiency OE can be expressed by, see Appendix B:

$$AE = 1 - u(1 - A) = 1 - \frac{t_0}{t_a} \cdot \frac{r}{1 - r} \tag{9}$$

$$OE = \frac{t_0}{t_a - t_0 \cdot \frac{r}{1 - r}} \tag{10}$$

In these equations r is rework percentage. From these equations it follows that the product of AE and OE is constant again, which means that OEE is constant and does not depend on the rework percentage. This is illustrated in Figure 3 for a rework percentage between 0 and 0.25.

Figure 3: Influence of rework on OEE , AE and OE

The conclusion from the previous examples is that OEE is not a performance measure to compare stand alone machines or workstations. OEE contains the influence of the environment as the example with the utilization showed and submetrics AE and OE have to be taken into account mostly as the examples with downtime and rework showed.

3 Equipment effectiveness E

An alternative for the OEE is equipment effectiveness E as proposed in [12]. E considers the equipment and its environment as a manufacturing system. This system executes the manu-

Figure 4: Equipment states

facturing function. In order to be able to perform the manufacturing function, the conditions enforced by the system have to be fulfilled. This means, for example, that skilled operators are needed to operate the machine(s), and the presence of sufficient consumables, sufficient support tools, and so on, is required.

In [5], the standby time includes idle time due to lack of input items. However, in the manufacturing system approach, the flow of items is considered to be an input of the manufacturing system, and this input cannot be designed by the supplier of the manufacturing system since it is not a part of the manufacturing system. If, for instance, the input flow of items is stopped and the system is able to perform its function, the system can be repaired, improved or redesigned without gaining effective capacity. Also Jeong classifies starvation of equipment as a separate equipment loss, next to operator unavailability [11]. Since an equipment is not to blame for its environment, two new equipment states have been defined: no-input state and no-output state, see Figure 4.

Equipment effectiveness E consists of three sub-metrics: yield Y , rate factor R and availability A . These sub-metrics are discussed briefly. The derivation of E and its sub-metrics is given in [12].

Yield Y is defined as the fraction of total items that have been manufactured and that meet the quality requirements of the manufacturer. Yield Y accounts for rework and scrap. This definition is in accordance with [4]. Yield is defined as the ratio of the number of qualified items N_Q to the total number of produced items N :

$$Y = \frac{N_Q}{N}$$

Rate factor R indicates the difference in actual speed compared to the maximum design speed of the equipment. The rate factor is the ratio of number of items N produced at the actual rate compared to maximum number of items $N_{\max}$ that can be produced at the specified maximum equipment rate:

$$R = \frac{N}{N_{\max}}$$

The third sub-metric of E is availability A . In [5] availability is defined as the probability that the equipment is in a condition to perform its intended function when required. The fraction of

effective time T_e that the system is able to perform its intended function is the availability:

$$A = \frac{T_0}{T_e}$$

The effective time T_e is always larger than the productive time T_0 .
Equipment effectiveness E can be written as the product of the three sub-metrics:

$$E = A \cdot R \cdot Y$$

In order to measure correctly the individual equipment states, a state diagram has been described by [12].

Equipment effectiveness E does not depend upon u :

$$E = A \cdot R \cdot Y = \frac{t_o}{t_e} \cdot R \cdot Y \tag{11}$$

When varying utilization u , E does not change as E is determined solely by equipment parameters. E will change only if the equipment dependent effective time is changed, e.g. because of an improvement or redesign of the equipment.

The measurements as given by Table 1 are used to compose Table 5. For these data the values of E are, see Table 6:

	A	B
total time	168h	168h
non-operational time	0h	0h
no-input time	72h	48h
no-output time	0h	0h
production time	84h	108h
total (un)scheduled down time	12h	12h
theoretical production time per unit	0.044h	0.044h
maximum throughput	22.73 /h	22.73 /h
number of items	1860	2324
number of qualified items	1810	2261

Table 5: Measured data set I

	A			B		
Y	1810/1860	=	0.973	2261/2324	=	0.973
R	1860/22.73 · 84	=	0.974	2324/22.73 · 105	=	0.974
A	84/(168-72)	=	0.875	105/(168-48)	=	0.875
E	0.973 · 0.974 · 0.875	=	0.829	0.973 · 0.974 · 0.875	=	0.829

Table 6: Results for E for data set I

The results show that E does not depend upon the utilization. To summarize the results, Figure 5 illustrates the dependence of OEE and E on utilization u .

Figure 5: Influence of u on OEE and E ($A=0.833$; $RE=1$; $QE=1$)

For the the influence of the down time, Table 7 is composed by using the values as given in Table 3. The values of E are shown in Table 8. The results show that E depends upon the down time. This is illustrated in Figure 6.

	A	C
total time	168h	168h
non-scheduled time	0h	0h
standby time	72h	60h
production time	84h	84h
engineering time	0h	0h
total (un)scheduled down time	12h	24h
theoretical production time per unit	0.044h	0.044h
maximum throughput	22.73 /h	22.73 /h
number of items	1860	1860
number of qualified items	1810	1810

Table 7: Measured data set II

	A			C		
Y	1810/1860	=	0.973	1810/1860	=	0.973
R	1860/22.73 · 84	=	0.974	1860/22.73 · 84	=	0.974
A	84/(168-72)	=	0.875	84/(168-60)	=	0.778
E	0.973 · 0.974 · 0.875	=	0.829	0.973 · 0.974 · 0.778	=	0.737

Table 8: Results for E for data set II

Figure 6: Influence of t_r on OEE and E

As has been derived in Appendix B, availability A depends on rework percentage r , so that E can be expressed by:

$$E = A \cdot R \cdot Y = (1 - r) \cdot R \cdot Y$$

The conclusion is that equipment effectiveness E is affected by rework and decreases linearly with rework while OEE is not affected by rework. Again, this is due to the fact that rework is defined as an equipment parameter.

To summarize the results, Figure 3 shows the dependence of r on OEE and E .

Figure 7: Influence of rework percentage on OEE and E

4 Comparison of OEE and E

The main difference between OEE and E is the approach of equipment: integrated or stand-alone. OEE measures the effectiveness of equipment including effects from other equipment in front of and at the end of the equipment of interest. This means that OEE does not monitor the equipment status, but a status consisting of effects caused by the equipment of interest and other equipment. E measures the effectiveness of stand-alone equipment in order to monitor the status of the equipment itself.

OEE nor *E* are diagnostic measures that indicate e.g. causes for low values.

The difference between *OEE* and *E* can also be expressed by the choice of the time base. Nakajima [2] takes the loading time as time base, being the available time per day, which is derived by subtracting the planned downtime from the total available time per day (or month). In [4] total time is used as time base, which is defined as all time (at the rate of 24 hours per day, seven days per week) during the period being measured.

In general, the time base should be the time period that equipment is enabled to perform its intended function without being limited by circumstances from outside. That means that only failures caused by the equipment should be accounted for by the equipment. The equipment is not responsible for equipment independent failures. If, for instance, item supply to the equipment is not possible, e.g. because of scheduling requirements, this failure is not caused by the equipment. In this case, the fab conditions may require such a scheduling but it should not be put on the account of the stand-alone equipment. Therefore, by using *E* the time base should not include idle time caused by lack of input items or any other equipment independent failure. This time base is the effective time.

Another result is that *E* does not depend upon utilization, as *OEE* does, but is measured directly by production time and effective time. Utilization is defined as the time fraction that the system environment allows the equipment to fulfil its intended function. Having effective time as base time means that *E* is based upon a measure that includes all time losses due to down, setup, or rework caused by the equipment itself.

5 Conclusions

The objective of the *OEE* is to have a metric showing the performance of equipment. However, *OEE* is not directed to equipment itself, but includes effects of the environment of equipment too. This is caused by viewing time losses because of lack of input items or no buffer space for items in the time base although this no-input or no-output situation cannot be put on the account of equipment. The derived system effectiveness *E* includes only events that are caused by the equipment itself s this metric is based on the effective time.

The influences of utilization, down time and rework on *OEE* and *E* are investigated. For the influence of utilization and rework, analytical relations are derived and discrete-event simulation models are built and used for evaluation. The sub-metrics availability efficiency and performance efficiency of *OEE* are also investigated. As these components are not mutually exclusive, *OEE* does not always show the influence of changes in equipment properties. In contrast, equipment effectiveness *E* does show these influences. Another difference between both performance measures is the fact that *OEE* is affected by the environment, whereas *E* is solely affected by the behavior of the equipment itself.

From a comparison it follows that the main difference between *OEE* and *E* is the approach of equipment: integrated or stand-alone. *OEE* measures the effectiveness of equipment including effects from other equipment in front of and at the end of the equipment of interest. This means that *OEE* does not monitor the equipment status, but a status consisting of effects caused by the equipment of interest and other equipment. *E* measures the effectiveness of stand-alone equipment in order to monitor the status of the equipment itself.

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A List of symbols

Symbol	Description
A	availability
AE	availability efficiency
E	manufacturing effectiveness
n	number of lots or products
N	total number of produced items
$N_{\max}$	maximum number of items that can be produced
N_Q	number of qualified items
OE	operational efficiency
p	probability that an item or lot has to be reworked
QE	quality efficiency
r	rework percentage
R	rate factor
RE	rate efficiency
t_a	interarrival time of items or lots
t_e	effective process time
t_o	natural process time
T_e	effective time
T_o	productive time
u	utilization
X_e	stochastic effective process time
Y	yield factor

B Rework

In this section, the influence of quality problems on OEE and its components is investigated. Analogous, the behavior of E for a system subject to quality problems is analyzed. Quality problems lead to either scrapped products and/or reworked products. Here, only rework is considered for a system without scrap.

It is assumed that the quality check is an integral part of the processing, and therefore possible product defects are known upon product completion. If a product is defective, it must be reworked. This is illustrated in Figure 8. The consequence is that rework affects utilization, since rework affects the effective process time as additional processing time is spent to get the job right. Note that variability is also affected by rework but this is not investigated here.

Figure 8: Single workstation flow line with rework

In this derivation of the EPT parameters, the natural process time t_0 refers to the natural process time for a machine. The effect on the realizations X_e of EPT when the machine goes

Figure 9: Gantt chart with EPT realizations

out of control is depicted in Figure 9. The natural process time t_0 (including measurement) equals one hour. Lot 1 is a qualified lot and therefore $X_{e,1}$ equals t_0 . During production of lot 2, the workstation goes out of control. After the processes and measurement have been finished, the out of control situation is detected and immediately lot 2 will be reworked. Lot 2 exploits capacity from the machine for 2 hours and therefore $X_{e,2}$ equals $2t_0$. When lot 2 has been reworked, lot 3 is started and finishes without problems and so $X_{e,3}$ equals t_0 .

The possible realizations for the random variable X_e can now be defined as:

$$X_e = \begin{cases} t_0 & \text{with probability } (1 - p) \\ 2t_0 & \text{with probability } p(1 - p) \\ 3t_0 & \text{with probability } p^2(1 - p) \\ \dots & \dots \end{cases} \quad (12)$$

If a lot is processed as a qualified lot with probability $1 - p$, X_e will equal t_0 . When an out of control situation occurs once with probability $p(1 - p)$, X_e will equal $2t_0$, etc. With these realizations and their probability of occurrence, the first moment of X_e , which equals the mean effective process time t_e , can be expressed as:

$$\begin{aligned} t_e &= (1 - p)t_0 + p(1 - p)2t_0 + p^2(1 - p)3t_0 + \dots \\ &= (1 - p)t_0 \sum_{n=0}^{\infty} \{(n + 1)p^n\} \\ &= \frac{1}{1 - p}t_0 \end{aligned} \quad (13)$$

$$u = \frac{t_0}{t_a \cdot (1 - r)}$$

This means that the utilization increases nonlinearly with rework. The equipment may have not enough capacity to keep up with both new arrivals and rework jobs over the long run [13]. The availability can be expressed by:

$$A = \frac{t_0}{t_e} = (1 - r)$$

Availability decreases if rework increases as items have to wait longer as more rework items have to be processed.

Now, Equipment Effectiveness E can be expressed by:

$$E = A \cdot R \cdot Y = (1 - r) \cdot R \cdot Y \quad (14)$$

OEE is not affected by rework as t_o and t_a are constant and not influenced by rework:

$$OEE = \frac{t_0}{t_a} \cdot RE \cdot QE$$

The sub-metrics AE and OE can be written as:

$$AE = 1 - u(1 - A) = 1 - \frac{t_0}{t_a} \cdot \frac{r}{1 - r} \quad (15)$$

$$OE = \frac{t_0}{t_a - t_0 \cdot \frac{r}{1 - r}} \quad (16)$$