International Journal of Production Research,
Vol. 44, No. 23, 1 December 2006, 4987–5003

OEE and equipment effectiveness: an evaluation

A. J. DE RON* and J. E. ROODA

Systems Engineering Group, Department of Mechanical Engineering,
Eindhoven University of Technology, P.O. Box 513,
5600 MB Eindhoven, The Netherlands

(*Revision received November 2005*)

The overall equipment effectiveness or efficiency (*OEE*) is a metric that has been accepted in the semiconductor industry. *OEE* is simple and clear, and standards and guidelines have been developed. Nonetheless, the literature indicates imperfections in applying *OEE* with regard to the time base and rate efficiency. As *OEE* lacks a proper framework, the equipment effectiveness (*E*) has been developed based on a systematic approach to the equipment. *E* considers the effectiveness of the 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 a basis in contrast to *OEE*, which uses the total time as a basis for measurement. Finally, due to the fact that *E* is measured directly by the 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 downtime and rework, whereas *E* gives these influences correctly.

Keywords: Performance measures; Operations management; *OEE*

1. Introduction

Performance measurement is a topic that is often discussed in the literature. Performance can be defined as the extent to which a company or process fulfill their objectives. Measuring the performance of a process provides information concerning the status of the process and enables decisions to be made concerning the adjustment of settings or actions to improve performance. Kaydos (1999) 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 communicating a company's strategy throughout the organization.

*Corresponding author. Email: a.j.d.ron@tue.nl

International Journal of Production Research
ISSN 0020–7543 print/ISSN 1366–588X online
http://www.tandf.co.uk/journals
DOI: 10.1080/00207540600573402

- Understanding business processes, since measuring data requires an understanding of the manufacturing process.
- Determining process capability, because understanding a process also means knowing its capacity.

A key performance measure in mass-production environments is the Overall Equipment Effectiveness (*OEE*). *OEE* was introduced by Nakajima (1988) in the context of Total Productivity Maintenance (TPM) and is directed towards equipment/machines. *OEE* is a simple and clear overall metric, and managers appreciate such an aggregated metric instead of many detailed metrics. Huang *et al*. (2003) report that the concept of *OEE* is becoming increasingly popular and that it has been widely used as a quantitative tool essential for the measurement of productivity in semiconductor manufacturing operations, because of 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 the definition and measurement of *OEE* as introduced by Nakajima (1988). The standard is directed towards 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 by SEMI (2000) and uses definitions as laid down by SEMI (2001). A guide for the application of *OEE* is described by Ames *et al*. (1995).

Previous research has targeted various aspects of *OEE*. For example, Ljundberg (1998) 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 labour. In addition, the available time would be a more appropriate basis for time measurement than the loading time as it was originally used by Nakajima (1988). Similarly, De Groote (1995) utilizes a fixed planned production time and calculates the difference between the actual and planned production time. The need for a more appropriate time basis is supported by Sattler and Schlueter (1998), Jonsson and Lesshammar (1999) and Jeong and Phillips (2001). It is generally observed that the accuracy of *OEE* is largely determined by the quality of the collected data.

The description given by Nakajima (1988) and SEMI (2000) is directed towards equipment, but *OEE* is impacted greatly by factors beyond the equipment itself, including the operator, recipe, facilities, material (input items) availability, scheduling requirements, etc. As this may result in *OEE* values influenced by factors beyond the equipment itself, a distinction can be made between stand-alone equipment and integrated equipment. *OEE* is directed towards equipment integrated in a manufacturing environment, so that *OEE* includes the influences of this environment.

As a metric was lacking directed towards stand-alone equipment, de Ron and Rooda (2005) proposed the equipment effectiveness E. This performance measure was derived to monitor the effectiveness of stand-alone equipment, independent of the environment.

The aim of this paper is to describe the behaviour of *OEE* and E as performance measures for manufacturing equipment. *OEE* is briefly described in section 2. In this section, the influence of equipment utilization, downtime and rework are also discussed. A description of equipment effectiveness E is given in section 3 as well as a description of the influence of utilization, downtime and rework. A comparison between the performance measures is given in section 4, and the conclusions are presented in section 5.

2. Overall equipment effectiveness

In considering OEE, Nakajima (1988) defines six large equipment losses.

1. Equipment failure/breakdown losses are categorized as time losses when productivity is reduced, and quality losses caused by defective products.
2. Setup/adjustment time losses result from downtime and defective products that occur when the 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 production is interrupted by a temporary malfunction or when a machine is idling.
4. Reduced speed losses refer to the difference between the equipment design speed and the actual operating speed.
5. Reduced yield occurs during the early stage of production from machine startup 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 the availability, V, of a machine. The third and fourth losses are speed losses, which determine the so-called performance efficiency, P, of a machine, i.e. the losses that occur as a consequence of 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 the quality rate, Q, of parts within the factory. OEE is measured as

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

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 the working time minus planned downtime, where downtime is the stoppage time loss due to breakdowns, setup and adjustments.

SEMI (2000) expresses OEE entirely in terms of time. SEMI (2001) defines six main states of manufacturing equipment (figure 1). Using these states, the following definition of the overall equipment efficiency can be given (SEMI 2000):

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

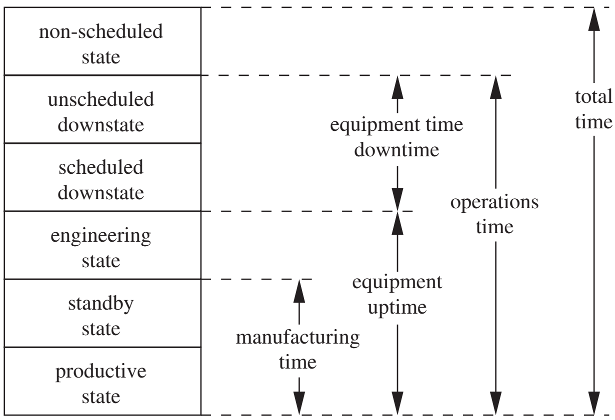

Figure 1. *OEE* equipment states.

OEE consists of availability efficiency *AE*, operational efficiency *OE*, rate efficiency *RE* and quality efficiency *QE*:

$$OEE = AE \cdot (OE \cdot RE) \cdot QE, \tag{1}$$

with

$$AE = \frac{\text{equipment uptime}}{\text{total time}}, \tag{2}$$

$$OE = \frac{\text{production time}}{\text{equipment uptime}}, \tag{3}$$

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

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

In these definitions, the theoretical production time is the production time at strictly theoretically efficient rates without efficiency losses.

The application of *OEE* is illustrated in the following examples. Table 1 shows the measurement data for the two situations. The difference between the situations is that, in case B, the throughput is larger than in case A so that the productive time is longer and more items are produced. Because of the longer production time, the downtime is increased and the standby time decreased as more capacity is required. The results are given in table 2.

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

The influence of the environment on *OEE* can be treated more generally by considering the utilization. This measure indicates the portion of the total time that the 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 the natural

Table 1. Measurement data set I.

	A	B
Total time (h)	168	168
Non-scheduled time (h)	0	0
Standby time (h)	72	48
Production time (h)	84	105
Engineering time (h)	0	0
Total (un)scheduled downtime (h)	12	15
Theoretical production time per unit (h)	0.044	0.044
Maximum throughput (h^{-1})	22.73	22.73
Number of items	1860	2324
Number of qualified items	1810	2261

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

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

process time t_0 (productive time/number of items) and the inter-arrival time t_a (total time/number of items):

$$AE\cdot OE=\frac{\text{production time}}{\text{total time}}=\frac{t_0}{t_a}. \tag{4}$$

For a particular manufacturing system, the product of AE and OE depends upon the utilization u:

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

In this equation the availability A and utilization u can be written in terms of the natural process time t_0, the effective process time t_e and the 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 that an item exploits capacity from the system, until it is processed as a qualified lot (Jacobs *et al*. 2003).

By substituting equation (5) into (1) we obtain

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

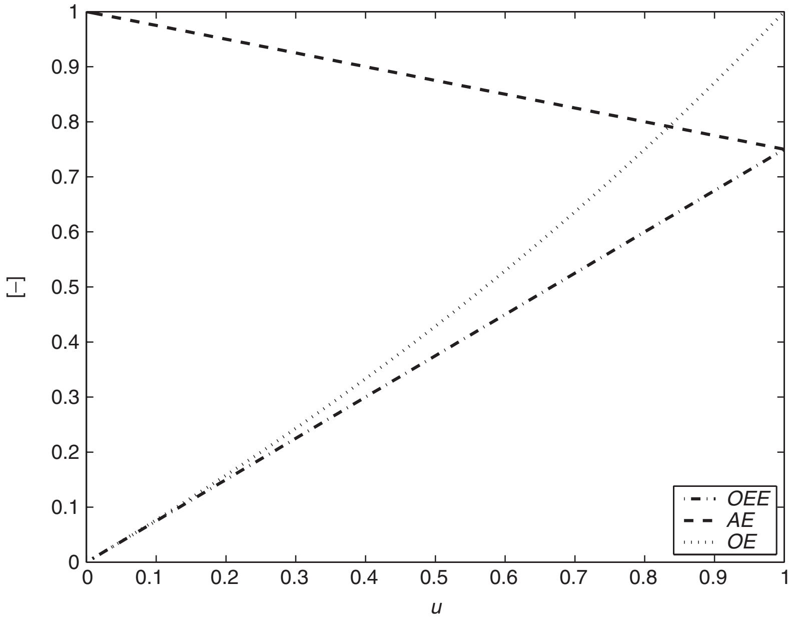

Figure 2. Influence of u on OEE, AE and OE ($A = 0.75$, $RE = 1$, $QE = 1$).

The dependence of OEE upon utilization u is determined by the sub-metrics AE and OE. Using equations (2) and (3) these sub-metrics can be expressed as

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

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

Equation (8) shows that AE and OE are mutually dependent. Figure 2 illustrates the dependence of OEE, AE and OE on utilization (see equations (6), (7) and (8)).

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

The second example concerns the influence of downtime (table 3). Case A is the base situation as given also in table 1. In case C the downtime has doubled so that the standby time has decreased. The results are given in table 4. Only the sub-metrics AE and OE are changed because of the increased downtime, but their product has not changed as the production time has not changed. As a consequence, OEE does not change in spite of the increased downtime.

The last example concerns equipment with rework. In the case of rework, availability efficiency AE and operational efficiency OE can be expressed as (see Appendix B)

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

$$OE = \frac{t_0}{t_a - t_0\cdot[r/(1-r)]}, \tag{10}$$

Table 3. Measured data set II.

	A	C
Total time (h)	168	168
Non-scheduled time (h)	0	0
Standby time (h)	72	60
Production time (h)	84	84
Engineering time (h)	0	0
Total (un)scheduled downtime (h)	12	24
Theoretical production time per unit (h)	0.044	0.044
Maximum throughput (h^{-1})	22.73	22.73
Number of items	1860	1860
Number of qualified items	1810	1810

Table 4. Results of *OEE* for 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	$1860\times 0.044/84=0.974$	$1860\times 0.044/84=0.974$
QE	$1810/1860=0.973$	$1810/1860=0.973$
OEE	$0.929\times 0.538\times 0.974\times 0.973=0.474$	$0.857\times 0.583\times 0.974\times 0.973=0.474$

where r is the rework percentage. From these equations it follows that the product of *AE* and *OE* is again constant, 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.

The conclusion from the previous examples is that *OEE* is not a good performance measure for a comparison between stand-alone machines or workstations. *OEE* includes the influence of the environment, as shown by the example with utilization, and sub-metrics *AE* and *OE* have to be taken into account, as shown by the examples with downtime and rework.

3. Equipment effectiveness *E*

An alternative to *OEE* is the equipment effectiveness *E* as proposed by de Ron and Rooda (2005). *E* considers the equipment and its environment as a manufacturing system. This system executes the manufacturing 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, etc., is required.

SEMI (2001) included the idle time due to lack of input items in the standby time. However, in the manufacturing system approach, the flow of items is

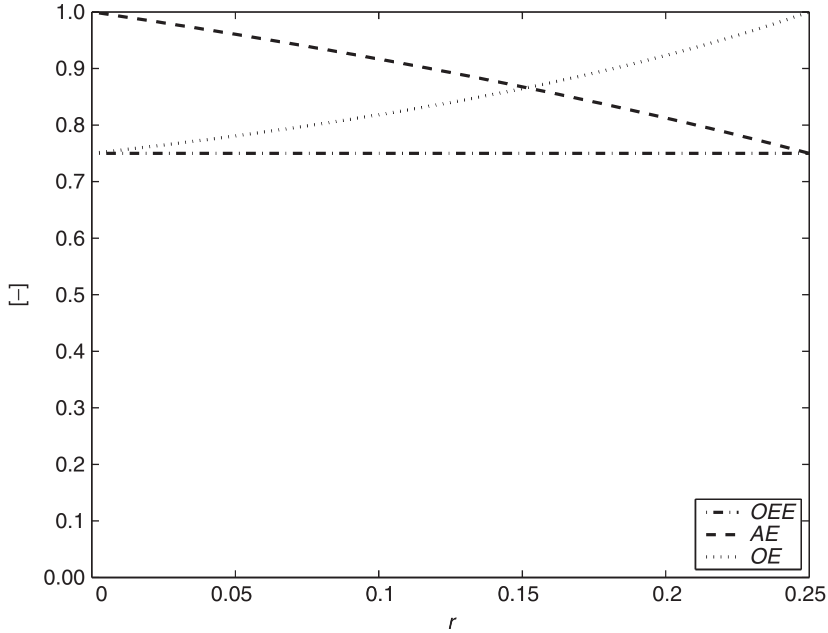

Figure 3. Influence of rework on *OEE*, *AE* and *OE* ($t_o/t_a = 0.75$, $RE = 1$, $QE = 1$).

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 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 and Phillips (2001) classify starvation of equipment as a separate equipment loss, as well as operator unavailability. Since a piece of equipment is not to blame for its environment, two new equipment states have been defined: the no-input state and the 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 by de Ron and Rooda (2005). Yield Y is defined as the fraction of total items manufactured that meet the quality requirements of the manufacturer. Yield Y accounts for rework and scrap. This definition is in accordance with SEMI (2000). Yield is defined as the ratio of the number of qualified items, N_{Q}, to the total number of items produced, N:

$$Y = \frac{N_{\mathrm{Q}}}{N}.$$

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

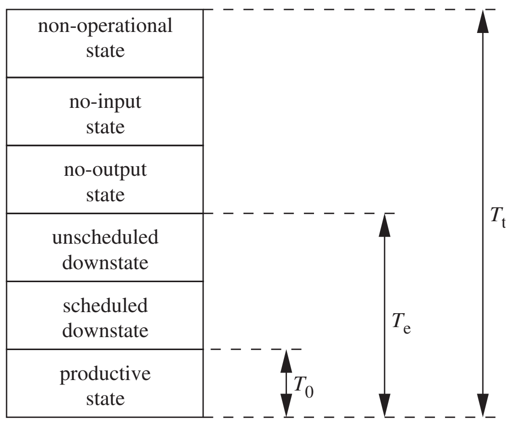

Figure 4. Equipment states.

produced at the specified maximum equipment rate:

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

The third sub-metric of E is availability A. SEMI (2001) defines availability 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 the individual equipment states correctly, a state diagram has been reported (de Ron and Rooda 2005).

Equipment effectiveness E does not depend upon u:

$$E = A \cdot R \cdot Y = \frac{t_0}{t_e} \cdot R \cdot Y. \tag{11}$$

When varying the utilization u, E does not change, as E is determined solely by equipment parameters. E will change only if the equipment-dependent effective time changes, e.g. because of an improvement or redesign of the equipment. The measurements given in table 1 were used to compose table 5. For these data the values of E are given in table 6. 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.

Table 5. Measured data set I.

	A	B
Total time (h)	168	168
Non-operational time (h)	0	0
No-input time (h)	72	48
No-output time (h)	0	0
Production time (h)	84	108
Total (un)scheduled downtime (h)	12	12
Theoretical production time per unit (h)	0.044	0.044
Maximum throughput (h^{-1})	22.73	22.73
Number of items	1860	2324
Number of qualified items	1810	2261

Table 6. Results for E for data set I.

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

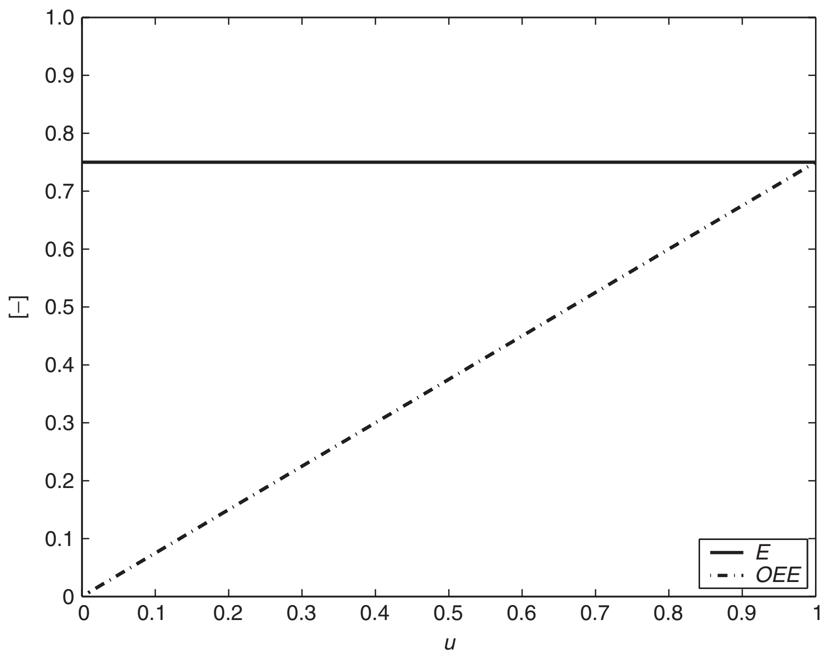

Figure 5. Influence of u on OEE and E ($A = 0.75$, $RE = 1$, $QE = 1$, $R = 1$, $Y = 1$).

Table 7. Measured data set II.

	A	C
Total time (h)	168	168
Non-scheduled time (h)	0	0
Standby time (h)	72	60
Production time (h)	84	84
Engineering time (h)	0	0
Total (un)scheduled downtime (h)	12	24
Theoretical production time per unit (h)	0.044	0.044
Maximum throughput (h^{-1})	22.73	22.73
Number of items	1860	1860
Number of qualified items	1810	1810

Table 8. Results for E for data set II.

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

For the influence of the downtime, table 7 uses the values given in table 3. The values of E are shown in table 8. The results show that E depends upon the downtime. This is illustrated in figure 6.

As shown in appendix B, availability A depends on the rework percentage r, so that E can be expressed as

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

The conclusion is that equipment effectiveness E is affected by rework and decreases linearly with rework, whereas 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 7 shows the dependence of r on OEE and E.

4. Comparison of *OEE* and *E*

The main difference between OEE and E is the equipment: integrated or stand alone. OEE measures the effectiveness of the equipment, including the effects from other equipment in front of and after the equipment of interest. This means that OEE does not monitor the equipment status, but a status consisting of the 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. Neither OEE nor E are diagnostic measures that indicate, for example, the causes of low values. The difference between OEE and E can also be expressed by the choice of the time base. Nakajima (1988) takes the loading time as the time base, being the available

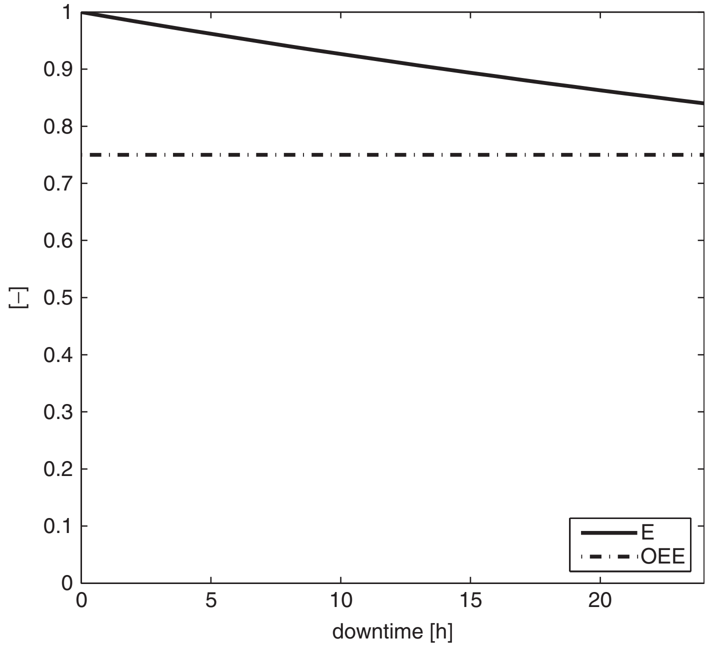

Figure 6. Influence of t_r on OEE and E ($t_o/t_a = 0.75$, $RE = 1$, $QE = 1$, $R = 1$, $Y = 1$).

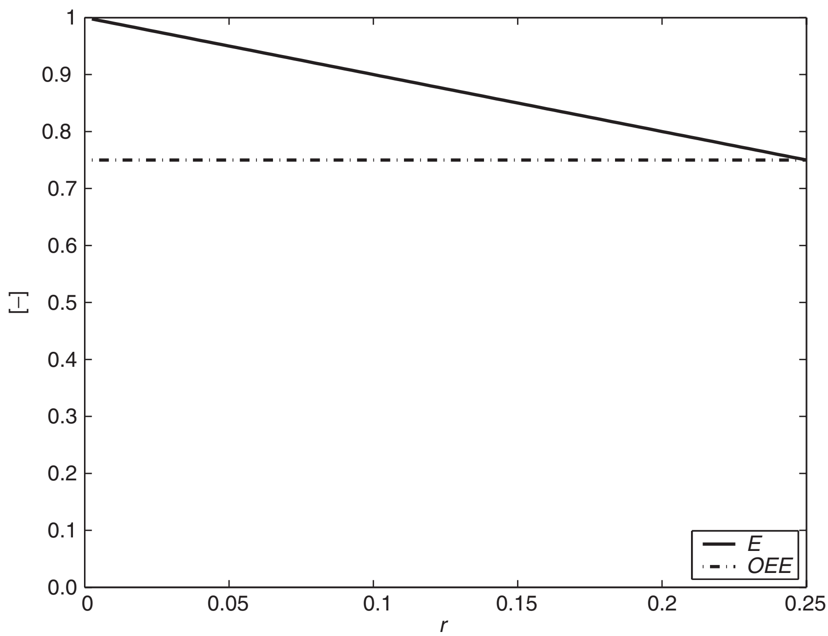

Figure 7. Influence of rework percentage on OEE and E ($t_o/t_a = 0.75$, $RE = 1$, $QE = 1$, $R = 1$, $Y = 1$).

time per day, which is derived by subtracting the planned downtime from the total available time per day (or month). SEMI (2000) use the total time as the time base, which is defined as all the time (at the rate of 24 h per day, seven days per week) during the period being measured. In general, the time base should be the time period that the equipment is able to perform its intended function without being limited by external circumstances. This 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, for example 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 the idle time caused by a 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, unlike OEE, but is measured directly by the production time and the effective time. Utilization is defined as the fraction of time that the system environment allows the equipment to fulfil its intended function. Having the effective time as the base time means that E is based upon a measure that includes all time losses due to downtime, setup, or rework caused by the equipment itself.

5. Conclusions

The idea behind OEE is to have a metric indicating the performance of equipment. However, OEE is not directed towards the equipment itself, but also includes the effects of the environment of the equipment. This is caused by viewing time losses, because of a 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 the equipment. The derived system effectiveness E includes only events that are caused by the equipment itself. This metric is based on the effective time.

The influence of utilization, downtime and rework on OEE and E has been investigated. For the influence of utilization and rework, analytical relations are derived and discrete-event simulation models are constructed 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 indicate the influence of changes in equipment properties. In contrast, equipment effectiveness E does show these influences. Another difference between the performance measures is the fact that OEE is affected by the environment, whereas E is solely affected by the behaviour of the equipment itself.

From a comparison it follows that the main difference between OEE and E is the approach to the equipment: integrated or stand alone. OEE measures the effectiveness of the equipment, including effects from other equipment in front of and after 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.

Appendix 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}	Inter-arrival time of items or lots
t_{e}	Effective process time
t_0	Natural process time
T_{e}	Effective time
T_0	Productive time
u	Utilization
X_{e}	Stochastic effective process time
Y	Yield factor

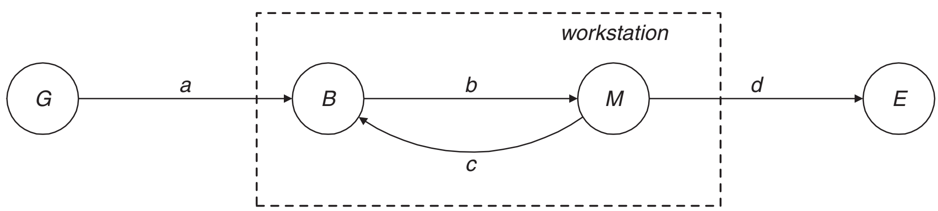

Figure B1. Single workstation flow line with rework.

Appendix B: rework

In this appendix, the influence of quality problems on OEE and its components is investigated. Analogously, the behaviour of E for a system subject to quality problems is analysed. 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 a 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 B1. The consequence is that rework affects utilization, since rework affects the effective process time, since additional processing time is spent to get the job right. Note that variability is also affected by rework but this is not investigated here.

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

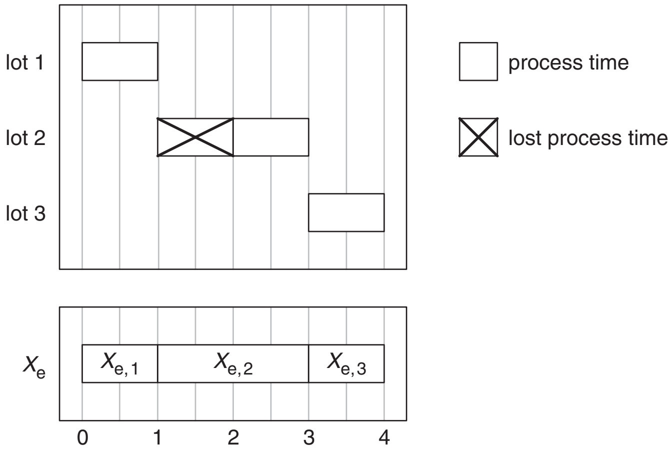

Figure B2. Gantt chart with EPT realizations.

machine goes out of control is depicted in figure B2. The natural process time t_0 (including measurement) is 1 h. Lot 1 is a qualified lot and therefore $X_{e,1} = t_0$. During the production of lot 2, the workstation goes out of control. After the processes and measurement have been completed, the out-of-control situation is detected and lot 2 is reworked immediately. Lot 2 exploits capacity from the machine for 2 h and therefore $X_{e,2} = 2t_0$. When lot 2 has been reworked, lot 3 is started and finishes without problems, therefore $X_{e,3} = t_0$.

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

$$X_e = \begin{cases} t_0, & \text{with probability } (1-p), \\ 2t_0, & \text{with probability } p(1-p), \\ 3t_0, & \text{with probability } p^2(1-p), \\ \dots & \dots \end{cases} \tag{B1}$$

If a lot is processed as a qualified lot with probability $1-p$, $X_e = t_0$. When an out-of-control situation occurs once with probability $p(1-p)$, $X_e = 2t_0$, 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

$$\begin{aligned} t_e &= (1-p)t_0 + p(1-p)2t_0 + p^2(1-p)3t_0 + \cdots \\ &= (1-p)t_0 \sum_{n=0}^{\infty} \{(n+1)p^n\} \\ &= \frac{1}{1-p} t_0, \end{aligned} \tag{B2}$$

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

This means that the utilization increases nonlinearly with rework. The equipment may not have sufficient capacity to keep up with both new arrivals and rework jobs over the long run (Hopp and Spearman 2001). The availability can be expressed as

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

Availability decreases if rework increases as items have to wait longer as more rework items have to be processed. Now, the equipment effectiveness E can be expressed as

$$E = A \cdot R \cdot Y = (1 - r) \cdot R \cdot Y. \tag{B3}$$

OEE is not affected by rework as t_0 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

$$AE = 1 - u(1 - A) = 1 - \frac{t_0}{t_a} \cdot \frac{r}{1 - r}, \tag{B4}$$

$$OE = \frac{t_0}{t_a - t_0 \cdot [r/(1 - r)]}. \tag{B5}$$

References

Ames, V.A., Gililland, J., Konopka, A. and Barber, H., *Semiconductor Manufacturing Productivity; Overall Equipment Effectiveness (OEE) Guidelines*, Technology transfer #950327443 A-GEN, Revision 1.0, 1995 (Sematech).

De Groote, P., Maintenance performance analysis: a practical approach. *J. Qual. Maint. Engng*., 1995, **1**, 4–24.

de Ron, A.J. and Rooda, J.E., Equipment effectiveness: OEE revisited. *IEEE Trans. Semicond. Manuf*., 2005, 190–196.

Hopp, W.J. and Spearman, M.L., *Factory Physics: Foundations of Manufacturing Management*, 2nd ed., 2001 (McGraw-Hill: New York).

Huang, S.H., Dismukes, J.P., Shi, J., Su, Q., Razzak, M.A., Bodhale, R. and Robinson, D.E., Manufacturing productivity improvement using effectiveness metrics and simulation analysis. *Int. J. Prod. Res*., 2003, **41**, 513–527.

Jacobs, J.H., Etman, L.F.P., van Campen, E.J.J. and Rooda, J.E., Characterization of operatinal time variability using effective process times. *IEEE Trans. Semicond. Manuf*., 2003, **16**, 511–520.

Jeong, K-Y. and Phillips, D.T., Operational efficiency and effectiveness measurement. *Int. J. Operat. Prod. Manage*., 2001, **21**, 1404–1416.

Jonsson, P. and Lesshammar, M., Evaluation and improvement of manufacturing performance measurement systems—the role of OEE. *Int. J. Operat. Prod. Manage*., 1999, **19**, 55–78.

Kaydos, W., *Operational Performance Measurement: Increasing Total Productivity*, 1999 (St. Lucie Press: Boca Raton, FL).

Ljundberg, O., Measurement of overall equipment effectiveness for TPM activities. *Int. J. Operat. Prod. Manage*., 1998, **18**, 495–507.

Nakajima, S., *Introduction to TPM: Total Productive Maintenance*, 1988 (Productivity Press Inc.: Cambridge, MA).

Sattler, L. and Schlueter, R., Semiconductor metrics: conflicting goals or increasing opportunities, in *1998 IEEE/SEMI Avanced Semiconductor Manufacturing Conference*, 1998, pp. 55–60.

SEMI, *Standard for Definition and Measurement of Equipment Productivity, SEMI E79-0200*, 2000 (Semiconductor Equipment and Material International: Mt. View, CA).

SEMI, *Standard for Definition and Measurement of Equipment Reliability, Availability and Maintainability, SEMI E10-0701*, 2001 (Semiconductor Equipment and Material International: Mt. View, CA).