Overall Input Efficiency and Total Equipment Efficiency

D. Daniel Sheu

***Abstract*—For years, overall equipment effectiveness (OEE) has been considered the ultimate efficiency index for production equipment, especially in the semiconductor industry where the equipment costs constitute some two-thirds to three-quarters of the total production costs. This paper asserts that the OEE is only half of the full efficiency equation. The concept of overall input equipment efficiency (OIE) is proposed to complete the full equation of the equipment efficiency. The multiplication of the OIE and OEE thus constitutes the true overall equipment efficiency which the author names total equipment efficiency (TEE) in order not to confuse with the current OEE. The importance of OIE with respect to OEE is explained. The differences between the well-known cost of ownership and the OIE/TEE are also explained.**

***Index Terms*—Cost of ownership (COO), equipment management, overall input efficiency (OIE), overall equipment effectiveness (OEE), semiconductor equipment efficiency, total equipment efficiency (TEE).**

I. Introduction

FOR YEARS, overall equipment effectiveness (OEE) has been considered the ultimate efficiency index for production equipment, especially in the semiconductor industry where the equipment costs constitute some two-thirds to three-quarters of the total production costs. However, for two pieces of the same type of equipment, it is possible that the output efficiency, OEE, may be the same but the consumption of the inputs such as labor, raw materials, consumables, etc., may be different. For example, it is not correct to judge the following two like machines as equal performers:

Machine A: (Owned by team AA)

Utilization 80%; Actual production rate: 10 pieces/hour; Ideal production rate: 10 pieces/hour; Yield: 99%; OEE $= 0.8 * 1 * 0.99 = 0.792$;
Raw work piece consumption rate: 10 pieces/hour; # of operators: 1 person / machine; Chemical consumption cost: \$1/piece; Power consumption: 3000 W; Spare parts replacement cost: \$1000/month;
Purchase cost: \$1.5 million;

Machine B: (Owned by team BB)

Except for the following items, all other performance indexes are the same:
# of operators: 0.5 person / machine; Chemical consumption cost: \$0.5/piece; Power consumption: 2000 W; Spare parts replacement cost: \$500/month;
Purchase cost: \$1.2 million.

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With the same output performance (thus the same OEE), machine B has been running much more efficiently than machine A in terms of input efficiency. Other things being equal, team BB has saved a great deal of money and should get better evaluation compared to team AA. It is apparent that OEE only takes care of the output side of machine efficiency. It is only half of the full equation. This paper proposes the concept and analysis of overall input efficiency (OIE) to complete the calculation of full machine efficiency which the author calls total equipment efficiency (TEE), in order not to be confused with the current OEE. The importance of OIE with respect to OEE are explained. The differences between the well-known cost of ownership (COO) and the OIE/TEE are also explained.

II. Literature Review

A. OEE

The concept of OEE was originated from Japan in 1971 [1]. The Japan Institute of Plant Maintenance promoted the total productive maintenance (TPM) which includes the OEE. In 1988, Nakajima introduced the TPM to the U.S. OEE has since gained a lot of attention as the ultimate performance measure of a piece of equipment. The term OEE was actually a misnomer. The true meaning should be overall equipment "efficiency" instead of "effectiveness." Efficiency and effectiveness have different meanings. Because the originator of the OEE named it as overall equipment effectiveness, the industry keeps the same wording although using it to refer to efficiency instead of effectiveness until the recent correction by SEMI E10 [2].

The SEMI International Standards Program is one of the key services offered by Semiconductor Equipment and Materials International (SEMI) for the benefits of the worldwide semiconductor and flat panel display (FPD) industries. In SEMI's definition of OEE (E79 [3]), the components of the OEE are described as follows:

$$\text{OEE}(\%) = \text{Availability Efficiency} \\ *\text{Performance Efficiency} * \text{Quality Efficiency}.$$

More related information regarding OEE can be found in [2] and [3].

B. COO

SEMI [4] in E35 defined "cost of ownership (COO) for semiconductor manufacturing equipment metrics." The goal is to measure the total cost of owning and operating the equipment over the equipment life cycle distributed over good outputs.

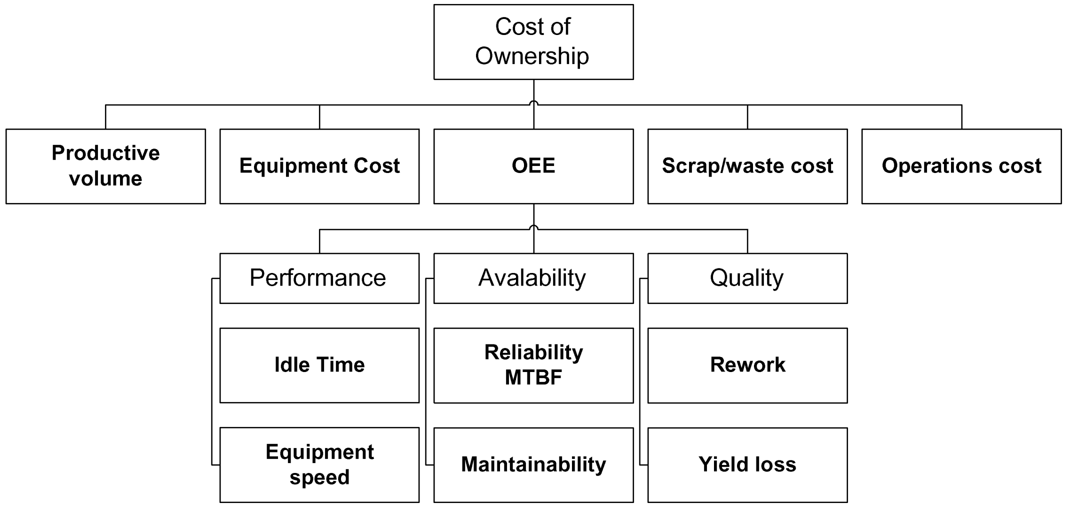

Fig. 1. OEE and COO relationship.

D. L. Dance *et al.* [5] asserted that equipment cost and OEE are two main determining factors for COO. They related the two concepts as listed in Fig. 1. It is clear that, other things being equal, the operational efficiency of a piece of machine on the output side, i.e., OEE, affects the number of good outputs produced over the equipment life cycle, thus entering the denominator of the COO calculation. By the same token, the proposed overall input efficiency of a piece of equipment, OIE, can affect the level of resources needed for the equipment to produce the same amount of good output, thus entering the calculation of the COO on the numerator side.

C. OIE

Much attention has been placed on reducing individual input resource requirements to reduce the manufacturing costs. No literature can be found to define and calculate the "integrated" overall efficiency on the input side—not to mention integrating the input and output efficiency to form the true overall equipment efficiency. This paper provides a systematic analysis of the overall input efficiency for a generic piece of equipment to enable the monitoring and management of the true overall equipment efficiency which the author calls TEE, in order to differentiate from the well-known OEE.

III. Theoretical Analysis

A. Total Equipment Efficiency

The well-known OEE includes the multiplication of availability, performance efficiency, and rate of quality [1]. The author asserts that the true overall equipment efficiency of a machine is the multiplication of equipment output efficiency with the equipment input efficiency. OEE is only the output side of the equipment efficiency. Output efficiency can be considered as actual output/ideal output given a reference level of nominal parts processed with the given piece of equipment. One unit of major work pieces, such as a wafer or a lot of wafers, can be used as the reference level of nominal parts processed as long as the reference level is kept consistent over the full period of study. On the contrary, the input efficiency can be considered as ideal input/actual input given the same reference level of nominal parts processed. Using the given level of nominal parts processed as the common reference point, we can multiply OIE with OEE to form TEE. The reason for defining "nominal" parts is to cover the most general cases when one may have n1 number of Part N1, n2 number of Part N2, ..., to form m number of product M. In this case, we can make any one of the constituent part Ni as the nominal part. As long as the nominal part and its nominal level are set the same on the input efficiency and output efficiency, OIE and OEE can be multiplied. For example, if four legs and one table face are to be processed into a table, we can use the processing of either four legs or one table face as the reference level of nominal part to measure both input efficiency (OIE) and output efficiencies (OEE) and the TEE can be obtained by multiplying OIE and OEE.

Fig. 2 shows the first level decomposition of TEE. Theoretically, the input items can include items shown on the left side of the figure such as acquisition cost, labor usage, raw material usage, consumable usage, facilities and utilities, and maintenance tool usage, etc. It is quite possible that two machines having identical output performance (OEE) can have quite different requirements on the input side as in the example cited in Section I of this paper.

The TEE is then the multiplication of the OIE with the overall output efficiency (OOE), which is commonly known as OEE. ($\mathrm{TEE} = \mathrm{OIE} * \mathrm{OEE}$)

$$\mathrm{TEE} = \mathrm{OIE} * \mathrm{OOE} = \mathrm{OIE} * \mathrm{OEE}.$$

B. OIE Analysis

Referring to Fig. 2, one can classify input resources to a piece of equipment in the following categories.

1) Facilities/Utilities: This includes water, power, air, etc.
2) Raw materials: This includes the base materials which serve as the work piece in the factories. Wafers are the raw materials in a typical fab.

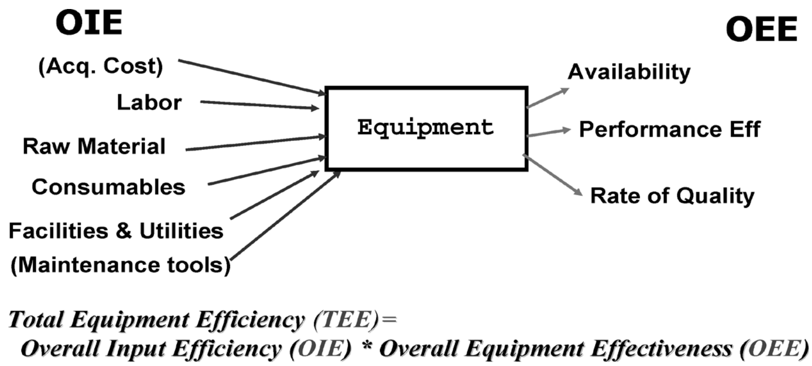

Fig. 2. TEE.

3) Consumables/spare parts: This includes all supporting consumable materials to support the production and the equipment spare parts which need to be replaced during the life time of the operations of the equipment.
4) Man power: The man power that is directly associated with the machine. This includes operator and technician times which may be directly associated with the piece of equipment. In certain cases, engineers' time may be considered in this category, if appropriate.
5) Nonrecurrent costs such as acquisition, training costs, etc.: Conceptually, the nonrecurrent costs are parts of the total inputs and can contribute to overall resource usage efficiency of the equipment. However, since the nonrecurrent costs are sunken once used, they may be excluded from the calculation of the OIE when the purpose is to measure the operational efficiency. One major usage of the OIE index is to evaluate the performance of the equipment usage. Sunken costs can distort the true performance evaluation of equipment manager during normal operations. In addition, many equipment owners may not even have any responsibility over acquisition costs which happened long before the person was in position. However, the nonrecurrent costs usually constitute a significant part of the overall equipment ownership costs. From the true meaning of "total" efficiency, it will not be fair to exclude the none-recurrent costs. As such, the author proposes two types of OIE and TEE indexes—one to handle the operational efficiency and the other to reflect the true overall costs for the usage of the equipment—as follows.
   a) $\mathrm{OIE}_p/\mathrm{TEE}_p$: This is used for operational performance when sunken costs are not considered.
   b) $\mathrm{OIE}_t/\mathrm{TEE}_{t.}$: This is used for true overall input efficiency considering the nonrecurrent sunken costs.

   Because most of the time when one measures OIE/TEE, the purpose is to measure the operational efficiencies, unless otherwise denoted for the true overall efficiency, OIE and TEE will be used to refer to $\mathrm{OIE}_p/\mathrm{TEE}_p$. Here, the subscript p signifies operational performance and t true efficiency. The author intentionally skips using "o" for the subscript as it is already used to signify "overall."
6) Maintenance tools: Maintenance tools are parts of overall all resources needed to utilize equipment. Conceptually, they can contribute part of input efficiency. In practice, usage efficiency of maintenance tools can be neglected as the tools are used across a large number of machines and can be used for a very long time. The amortization of maintenance tools upon any piece of equipment may be insignificant and difficult. Therefore, they can be dropped out of the OIE calculations in almost all practical usage. If, however, the maintenance tool cost is significant, we can include it for the calculation of the true input efficiency.

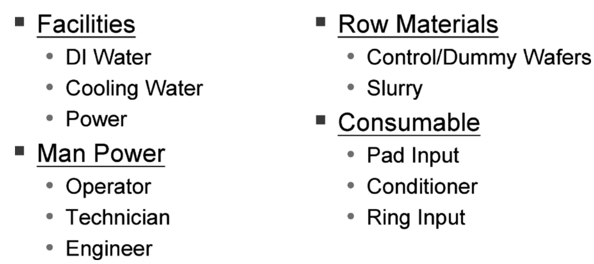

Fig. 3. Sample input classification for CMP.

For the purpose of calculating the management efficiency of a piece of equipment, items 5) and 6) mentioned previously are excluded from OIE. A generic first level of input resources can be divided into four categories: facilities, raw materials, manpower, and consumables.

Each category of the OIE can be further divided into subcategories. If needed, the subcategories may also be further divided into sub-subcategories, and so on. The OIE can be calculated by the compilation of the efficiencies for all the constituent subcategory items described in the next session. An example of first and second levels of input resources for a chemical–mechanical polisher (CMP) is given in Fig. 3 [6].

C. Calculation of OIE

Assume that there are I categories of inputs denoted as I_i, whose resource usage efficiency can be denoted as e_i. The relative importance of the input I_i *can be* denoted as w_i.

Then, the OIE of the corresponding equipment can be calculated as

$$\mathrm{OIE} \equiv \sum_{i=1}^{I} w_i e_i \quad i = 1, \ldots, I.$$

where i is the ith item of the first level resource inputs to the subject equipment

$$\sum_{i=1}^{I} w_i = 1.$$

The input efficiency of the item I_i, $e_{i.}$ can be defined as

$$e_i \equiv D_i / A_i$$

where:

A_i actual resource input level for item i;

D_i theoretical ideal resource input level for item i.

For example, if the theoretical minimum ideal consumption of photoresist is 0.015 c.c. and the actual spread is 3 c.c., then the input efficiency for the photoresist usage is $0.015/3 = 0.05 = 5\%$.

The relative weights w_i for all the categories of the same level have to add up to an unity. Various ways of determining relative weights can be used to support manager's equipment usage strategy. For example, one can emphasize reduction in the consumption of a certain chemical for long-term environmental concerns by putting extra weight on that item. Although other ways of assigning relative weights may be appropriate, the author proposes to use the relative resources needed in monetary value as a convenient and sensible measure. To standardize the calculations, one may aggregate the relative item costs for all similar machines of a particular type to determine the relative weights of the input items for that machine type.

In most cases, the classification of inputs may be expanded into more levels of hierarchy than the first level categories described in Section III-B. Each main level of efficiency e_i can be further divided into several second-level input efficiencies, etc. The higher level of efficiency can be calculated from its lower level constituents as follows:

$$e_i \equiv \sum_{j=1}^{J} w_{ij} e_{ij}$$

where j is the running index for the constituent lower level decomposition of the input resource i

$$\sum_{j=1}^{J} w_{ij} = 1$$

where w_{ij} is the weight for the input item I_{ij} with efficiency e_{ij}.

The same idea can apply on further lower levels of input constituents, if further decompositions of the input resources are needed. A sample of a detailed decomposition and calculations of OIE for CMP machines in a Taiwanese fab can be found in [6]. More complete indexes related to equipment management can be found in [7].

D. OIE Versus OEE Calculations

It is noted that the composition of OIE is the weighted addition instead of multiplication as in the OEE case. The differences between OEE and OIE are as follows.

1) The factors in OEE all have multiplicative impacts on the output production results. The calculation of the loss of efficiencies is sequential. Therefore, they multiply together to figure out the OEE. In the OIE case, all factors in the same level act in parallel. The loss on one factor does not affect others on the same level. The required resource needed is the simple addition of resource needs on all factors in the same level. For example, the efficiency loss on the photoresist spray has nothing to do with the exposure efficiency on the UV shots. Therefore, the efficiency loss on each item is localized in calculating OIE.
2) There is a relative weight associated with each input factor. As all input resources assume different units and consume different resources, a simple average of various input efficiency cannot reflect the correct overall input efficiency. A relative weight is needed to account for the different relative importance among the input resources on the same category of resources. For example, both the total cost and the unit price of photoresist are much more expensive than those of electric power. Therefore, relative expenses are recommended for determination of the relative weights. After all, all input resources can be converted into money spent on those inputs.

E. Importance and Usage of OIE

The impacts and usage of OIE can be described as follows.

1) \$1 cost saved versus \$1 revenue gained.
Pure improvements on the OEE side produce more good products in a shorter period with the same resources consumed. The result is the addition on the revenue side. Improvements on the OIE side reduce input costs with the same output. Other things being equal, one dollar saved in OIE is a dollar contributed to the final profit. Yet, one dollar's worth of product added on the output side may need more effort to push the added sales through, thus consuming some associated costs to partially offset the revenue gained.
2) OEE has gained much heavier attention than OIE.
Since the inception of OEE, heavy attention has been paid to it. Therefore, much gain has been made in the area. The room for further study is more limited. On the contrary, there have only been scattered individual efforts to reduce the input waste. To the best of author's knowledge, there has not been any significant effort to work on the systematic evaluation of the overall input efficiency, and the study on the ideal input level is rarely found. From the academic viewpoint, the author believes that the opportunities for research in this area are much greater than OEE.
3) OEE usually is much higher than OIE.
Based on the author's benchmarking of I.C. manufacturing performance of some ten fabs in Taiwan from 1997 to 2002, best-in-class OEE seems to be in 60%–70% at the

TABLE I
COMPARISON OF COO AND OIE/TEE

	Cost Of Ownership	Total Equipment Efficiency	Overall Input Efficiency
Usage	Used at the time of purchase decision for the calculation of the lifetime cost of a machine per good output.	Used to evaluate the usage efficiency of a machine against certain ideal standard in a given time period.	Used to evaluate the resource usage efficiency of a machine against certain ideal standard in a given time period..
Features	■ One-time estimate at the time when cost estimate is needed. ■ Hard to consider price fluctuation of input resources in the future. ■ Directly linked to bottom line. Good for estimating profit-loss of the machine operation over its lifetime. ■ No indication of management performance on equipment resources management for a given period. ■ Does not have diagnostic function. ■ Can not show individual resource usage efficiency of the equipment.	■ Evaluation of machine usage efficiency for any given periods throughout its useful life. ■ Single index for simple overall efficiency indication to represent combined result of OIE & OEE. Used to augment, but not replace OIE and OEE due to loss of granular evaluation of the usage efficiency. ■ Does not have diagnostic function to pinpoint the week areas. ■ Can decouple the effect of the uncontrollable market price fluctuation and measure the management performance directly.	■ Evaluation of machine efficiency for any given periods throughout its useful life. ■ More precise measure of resource usage efficiency for any given time period. ■ Multi-attribute presentation. Can show individual weakness/strength of resource usage. Easier to pinpoint relative importance of improvement opportunities. (Diagnostic function) ■ Can decouple the effect of the uncontrollable market price fluctuation and measure the management performance directly. ■ Can link to raw measurement units or monetary term. When the unit costs and life-cycle efficiency distribution are known, OIE can convert into COO. (accumulation of OIE over equipment lifetime affects the numerator side of the COO.)

time when the equipment utilization is good. Although no systematic measurements of OIE are available, out of some 50 visits to the factory floors in various fabs, the author has observed that typical input efficiency for some consumables such as photoresist or chemicals easily fall below 20%. In a true example, a 300-mm wafer sprayed 2.2 c.c. of photoresist only to retain some 80 nm of the thickness on the wafer. This is equivalent to 0.26% of the input efficiency: $(80 * 10^{-7}\ \mathrm{cm} * \pi * (15\ \mathrm{cm})^2/2.2\ \mathrm{cm}^3 = 2.57 * 10^{-3} = 0.257\%)$. Another real example on a 6-in wafer retained only 1.18% of input by keeping 800 nm of photoresist thickness after a spray of 1.2 c.c. of photoresist.

4) The coming age of low-profit-margin makes OIE important.
In the age of low-profit margins, every cent is important in manufacturing. When OEE is approaching its limit, waste minimization becomes an important differentiator for a company to differentiate itself from its competitors.

5) Usage for factory diagnostics.
By measuring OIE, management can locate the low-efficiency areas of the equipment operation, thus focusing the efforts on the weakest machines and the most influential waste of machine inputs. By benchmarking the major broken-down components of TEE of the like machines, management can locate the relative problematic areas of each machine, thus providing some clues for improvements for both product manufacturer and equipment manufacturer. Usually, the weakest areas are the low-hanging fruits for improvements. Note that benchmarking of OIE, or even OEE, should be limited to the same type of machines. Great caution should be exercised if one does intend to cross-benchmark different machines or benchmark a set of machines versus another set of machines.

F. OIE Versus COO

OIE and COO are two distinct concepts with different usage. COO represents the total cost of operating the equipment in its life cycle per good part. Its best usage is for the selection and evaluation of the equipment at the purchase time. OIE is used to evaluate the usage efficiency of a piece of equipment. The main purpose is to evaluate equipment usage performance over an observed period of time. The strength and usage of the two concepts are compared in Table I.

G. Determining Ideal Value of Input Resource

Determining the ideal value of an input resource with respect to reference level of nominal parts processed may not be straightforward in calculating OIE. In practice, the author recommends the following methods to determine the standard ideal input.

1) Use the theoretical physical value when all inputs are used toward the creation of the output without any waste of the input resource. This can be calculated by full reaction of chemical reaction formula or the retained materials after the process. For example, the remains of photoresist after the spray can be considered as the theoretical physical value of the photoresist. Also, the final deposited mass on a thin film can be used as the theoretical value for the

input resources using the corresponding chemical reaction formula.

2) When the theoretical physical value is not available, a benchmarking method can be adopted. If the theoretical value is not available, the best individual value ever occurring for any similar equipment can be used as the ideal standard. In this case, the ideal standard should be tightened when the best record is broken. The ratio between the two best records should be noted for future comparisons or rectification of the previous efficiency values due to the tightened standard.

The identification of the standard ideal input value is an area open for further research. The author will provide a separate paper to analyze the standard value for operator and maintenance technician resources [8]. Excel-based spreadsheet tools can be developed to facilitate calculations of TEE and provide suggestive improvement ideas for practical usage [6], [9]. An example of classification and spread sheet calculations of OIE/OEE/TEE for stepper machines can be found in [9].

IV. Conclusion

This paper rectified the myth of considering the OEE as the total efficiency of a piece of equipment. The concept and theory of OIE was introduced. The true overall equipment efficiency should be the multiplication of the OIE and OEE which is then termed the TEE. The importance of OIE and its differences with COO were explained. Two practical ways to determine the theoretical ideal value for any input resource were proposed. The main contributions of the paper include the following.

1) Providing another half of the true TEE with theoretical analysis. OIE can also provide opportunities for productivity improvements, even more so than OEE.
2) Identifying a new area for research in OIE analysis, especially on the determination of ideal standard input values.

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