Operational efficiency and effectiveness measurement

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Abstract *The accurate estimation of equipment utilization is very important in capital-intensive industry since the identification and analysis of hidden time losses are initiated from these estimates. In this paper, a new loss classification scheme for computing the overall equipment effectiveness (OEE) is presented for capital-intensive industry. Based on the presented loss classification scheme, a new interpretation for OEE including state analysis, relative loss analysis, lost unit analysis and product unit analysis is attempted. Presents a methodology for constructing a data collection system and developing the total productivity improvement visibility system to implement the proposed OEE and related analyses.*

Introduction

Total productive maintenance (TPM) is a people-intensive, preventive maintenance system for maximizing equipment effectiveness and which involves all departments and functions in the organization. The concept of TPM was originally suggested by Nakajima (1988) who proposed overall equipment effectiveness (OEE) as a metric for evaluating the progress of TPM, which is interpreted as the multiplication of availability, performance and quality. One of the important contributions of OEE was to consider equipment's hidden losses in computing equipment utilization. Before the advent of OEE, only availability was considered in equipment utilization, which resulted in the overestimation of equipment utilization (Ljungberg, 1998).

The accurate estimation of the equipment utilization is very important in capital-intensive industries (e.g. the semiconductor and chemical industries) since managers in these industries want to utilize their equipment as effectively as possible to get an early return on their investment. Based on the utilization estimated, managers can identify the causes of the time losses and attempt to reduce these losses. The original definition of OEE suggested by Nakajima is not appropriate for capital-intensive industry in that this version of OEE started to compute the time losses from the loading time, which does not include scheduled maintenance time for preventive maintenance and nonscheduled time such as off-shift and holiday. These time losses are, however, important in capital-intensive industry. For example, to reduce nonscheduled time, most semiconductor manufacturers are operating three eight-hour shifts with four groups where one group is off-shift while the other three groups are on-shift. The high setup time cost is another reason why capital-intensive industry should try to minimize nonscheduled time since frequent stoppages of the equipment require expensive warm-up time and cost.

One of the recently developed OEE application systems is the Capacity Utilization Bottleneck Efficiency System (CUBES), which is dedicated to the semiconductor industry (Konopka and Trybula, 1996). CUBES computes OEE as well as throughput lost during the computed time losses for the specific equipment. CUBES was constructed on the total calendar time-based approach instead of loading time-based approach. While the successful implementation of CUBES in the semiconductor industry is sufficient to motivate research of OEE within that industry, there is little research on the utility of OEE for other capital-intensive industries. Of the little research available, most authors adopted Nakajima's loss classification without further discussion. For example, Ljungberg (1998) and Raouf (1994) adopted Nakajima's six big loss classifications in their OEE computations. We believe, however, that loss classification schemes are ultimately tied to the industry type. The detailed loss classification scheme presented in this paper targets the capital-intensive industry. Based on our classification scheme, we also provide a new interpretation of OEE by categorizing the losses, and we attempt to enhance CUBES by allowing for simultaneous comparisons of multiple equipment at multiple performance measures.

Review and background

Based on his observations in Japan, Nakajima (1988) suggested the following six big time losses:

1. equipment failure;
2. setup and adjustment;
3. idling and minor stoppages;
4. reduced speed;
5. defects in process; and
6. reduced yield.

According to Nakajima, (1) equipment failure and (2) setup and adjustment were categorized as downtime time loss, reducing availability; (3) idling and minor stoppage and (4) reduced speed were categorized as speed loss, thus reducing performance. Finally, (5) defects in process and (6) reduced yields were considered as defect loss generated from low quality. As discussed above, Nakajima's measurement of OEE starts from calculating loading time by excluding planned unavailable time such as scheduled maintenance time and off-shift from the theoretic calendar time. Once the loading time is computed, the operating time (by excluding the time losses due to items (1) and (2) from the loading time), the net operating time (by excluding the time losses due to items (3) and (4) from operating time) and the valuable operating time (by excluding time losses due to items (5) and (6) from the operating time) are successively computed (Figure 1). The multiplication of availability, performance and quality results in

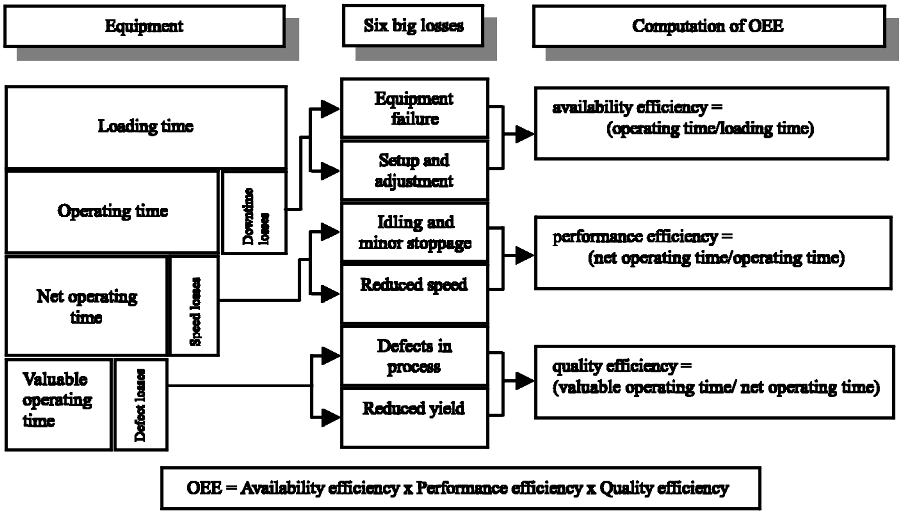
$$\mathrm{OEE} = \frac{\text{valuable operating time}}{\text{loading time}} \qquad (1)$$

Equation (1) can be used to roughly estimate OEE without collecting all six loss categories. Loading time is the total time available for production in a given period and valuable operating time can be estimated by multiplying the theoretical cycle time by the number of products that are successfully completed.

When considering that most of the capital-intensive industries use multiple shifts to improve equipment utilization, the use of loading time in equation (1) may not reflect the real equipment utilization. This is why the total calendar time-based approach is preferable to a loading time-based approach. The total calendar time-based approach uses theoretical calendar time in estimating OEE. For example, if one week is the time period of interest, the total theoretical time referred to as total time is 24 (hr/day) × 7 (days/wk) = 168 hr/wk. In Figure 1, it should be noted that performance efficiency includes both direct time loss such as idle and minor stoppage, and relative time loss such as reduced speed.

Taxonomy

It is apparent that the successful computation of OEE depends on the ability to collect data. If the data collected are unreliable, the OEE value computed may not reflect real equipment utilization. It is also important to recognize that each



Source: Nakajima (1988)

Figure 1.
OEE and computation procedure

loss classified corresponds to an equipment state. For example, if we are interested in the scheduled maintenance time for a machine, the data must be collected when the machine is in a state of scheduled maintenance. In computing OEE, each company may require different equipment states due to the level of accuracy and their data collection ability. However, the loss classification (equipment state) presented in this paper serves as a template for any capital-intensive industry. Based on SEMI E10-92 (1992) in previous research efforts, we say there are ten classifications of equipment losses:

1. *Nonscheduled time*: time duration for which equipment is not scheduled to operate. This time may include holiday and leave, etc.
2. *Scheduled maintenance time*: time spent for preventive maintenance in the equipment.
3. *Unscheduled maintenance time*: time spent for breakdown.
4. *R&D time*: time spent for the purpose of research and development.
5. *Engineering usage time*: time spent for an engineering check up.
6. *Setup and adjustment time*: time spent for setup and adjustment for operation.
7. *WIP starvation time*: time for which equipment is operating when there is no WIP to process.
8. *Idle time without operator*: time for which WIP is ready, however there is no operator available.
9. *Speed loss*: time loss due to the equipment that is operating under the standard speed.
10. *Quality loss*: time for which equipment is operating for the unqualified products.

As discussed above, both (1) nonscheduled time and (2) scheduled maintenance time are included to avoid overestimation of OEE. Scheduled maintenance time seems to have trade-off relation with unscheduled maintenance time. Hence, increasing (2) scheduled maintenance time to a certain extent decreases the unscheduled maintenance time. In general, the data collection for unscheduled maintenance time requires considerable time and cost. Alternatively, the following equation (2) can provide a reasonable estimate of unscheduled maintenance time using the mean time between failure (MTBF) and the mean time to repair (MTTR).

$$\text{Unscheduled maintenance time} = \text{theoretical calendar time}/\text{MTBF} \times \text{MTTR} \tag{2}$$

As the product life cycle shortens, the time required for (4) R&D has a tendency to increase. Because of the high cost in purchasing the dedicated equipment for (4) R&D and (5) engineering usage, most companies use the same equipment for production, research and engineering. Hence, these times should be considered in OEE. Mileham *et al.* (1997) reported that the effect of (6) setup and adjustment time on OEE increases significantly in multi-product manufacturing environments. However, he also noted that a too rigid emphasis on OEE might unduly influence a business toward mass manufacturing. Hence, a proper compromise is necessary between OEE and setup and adjustment. Suehiro (1992) has shown that idle and minor stoppage time is 20-30 percent of OEE in most automated lines, and Leachman (1995) observed that both (7) WIP starvation time and (8) idle time without operator were the most significant components of the idle and minor stoppage. As a consequence, both are separately considered in this paper. Note that WIP starvation time is mainly caused by the difference in production capacity between predecessor and successor processes. The concepts for (9) speed loss and (10) quality loss correspond to the speed loss and defect loss, respectively, in Nakajima's concept.

Data collection methodology

As discussed in the previous section, the quality of data collected determines the accuracy of OEE estimated. To collect qualified data, the use of the computerized data collection system is recommended in spite of high investment cost (Ljungberg, 1998). However, it should be noted that to effectively use the computerized data collection system, definite clarification between equipment states should be defined. Thus, the methodology for designing the data collection system is a significant point of discussion.

Note that each data loss for OEE will be collected when the equipment is in the corresponding state (loss classification) – a collection of variables that contain necessary information to describe the system. Hence, the boundary of each state must be clearly defined in order to collect reliable data. The boundary of each state can be described in terms of two conditions: the entry condition to the state and the exit condition from the state. The time loss at each state is known as the sojourn time in the state, which is the time between realization of the entry and exit conditions. From the discrete event dynamic system (DEDS) standpoint, this sojourn time is referred to as an activity, and all occurrences that cause the state change in equipment are referred to as events. For example, the part-loading event by an operator changes the state of equipment from idle to busy. Thus, for the successful implementation of the data collection system, all events required to perform the given operations in a machine must be defined. Once these events are defined, the state transition matrix – which describes what events activate the transition from the state i to state j – can be built. Note that state transition matrix describes the behavior of the data collection system on the high level. For example, suppose that an event (E_{ij}) occurs in a system and that this event changes the state of equipment from S_i to S_j. At this point, the data collection system has to recognize when both the exit condition of S_i and the entry condition of S_j are activated. Then, the sojourn time in the state is computed.

Analysis method

In this section we describe two computational methods for OEE – OEE 1 and OEE 2 – based on the theoretical calendar time-based approach, along with a brief discussion of throughput analysis. These two methods assume, as outlined in the previous section, that data have been successfully collected on each equipment state.

OEE 1 attempts to separate direct time losses from the relative time loss by classifying all time losses into three categories: total time loss, speed loss, and quality loss. All time losses corresponding to items (1) nonscheduled time through (8) idle time without operator are categorized as the total time loss because these are the direct production time losses which are used to compute the time efficiency. The procedures for computing OEE are shown in Figure 2.

OEE 1 is computed by multiplying time efficiency, speed efficiency and quality efficiency.

OEE 2 uses the same loss categorization as in Nakajima's approach. Thus, OEE 2 is the multiplication of availability, performance, and quality (Figure 3).

Using Figures 2 and 3, OEE can be represented as

$$\text{OEE} = \frac{\text{valuable production time}}{\text{total time}} \tag{3}$$

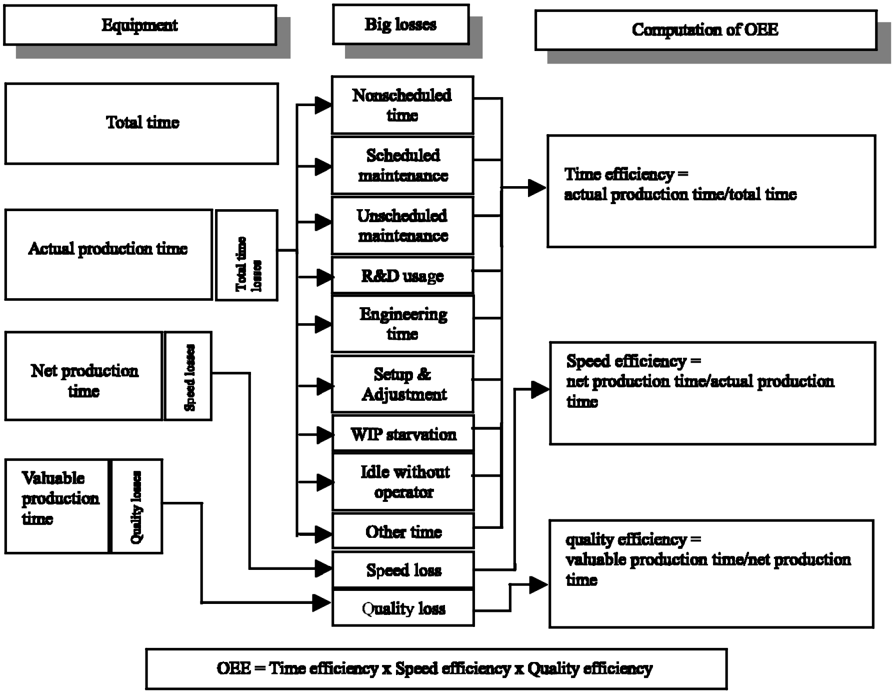


Figure 2.
OEE 1 and computation procedure

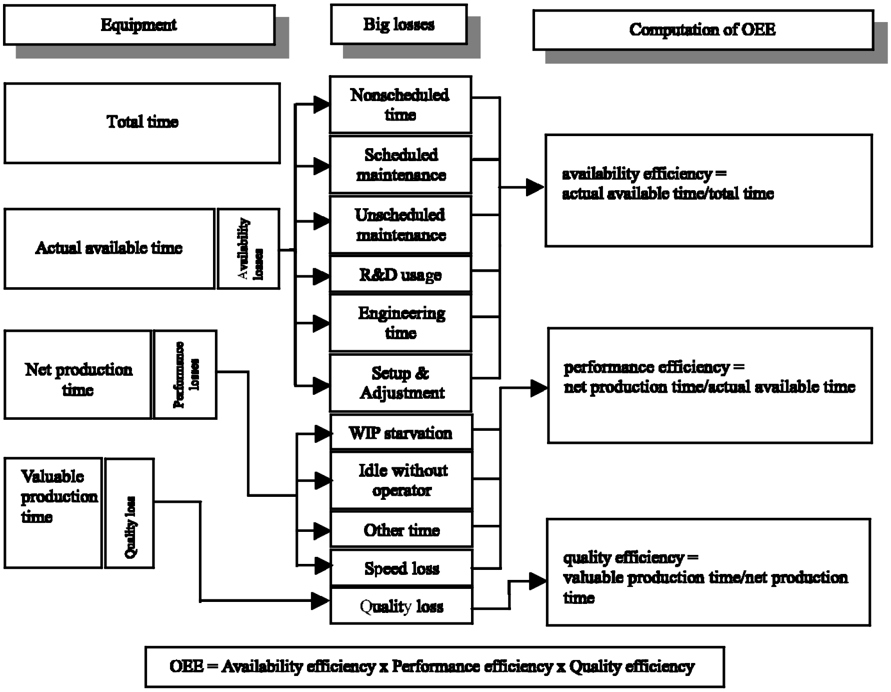


Figure 3. OEE 2 and computation procedure

Lost unit analysis is a type of throughput analysis that involves the computed time loss. The analysis estimates the number of lost units during any specific time loss and shows the number of possible or achievable units that may be accomplished if there are no time losses. For example, total unit lost is computed by multiplying any time loss by tool speed as seen in equation (4).

$$\text{Total unit lost} = \text{time loss} \times \text{tool speed} \tag{4}$$

Tool speed is represented by units per time. From equation (4), the number of good units lost can also be estimated using equation (5).

$$\text{Good unit lost} = \text{time loss} \times \text{tool speed} \times (1 - \text{current quality loss}) \tag{5}$$

where the current quality loss is the ratio of the number of good products to the number of products produced.

Further, if the value of WIP is known, the lost profit or opportunity cost can be estimated by multiplying the number of WIP lost by the WIP value.

Theoretical calendar time (total time) is used to estimate the maximum possible units, possible units, and achievable units. The maximum possible number of units is determined by multiplying the theoretically possible unit by the total time.

$$\text{Maximum possible number of units} = \text{total time} \times \text{theoretical tool speed} \tag{6}$$

The possible number of units is determined by multiplying the total time by the current tool speed, which would be slower than the theoretical tool speed.

$$\text{Possible number of units} = \text{total time} \times \text{current tool speed} \tag{7}$$

The achievable number of units can be determined by multiplying the possible number of units with the current quality loss.

$$\begin{aligned}&\text{Achievable number of units} = \text{total time} \times \text{current tool speed} \times \\ &(1 - \text{current quality loss})\end{aligned} \tag{8}$$

The quality loss units, which computes the number of products lost due to quality problems during the actual production time, can be determined by

$$\begin{aligned}&\text{Quality loss units} = \text{actual production time} \times \text{ current tool speed} \times \\ &\text{current quality loss}\end{aligned} \tag{9}$$

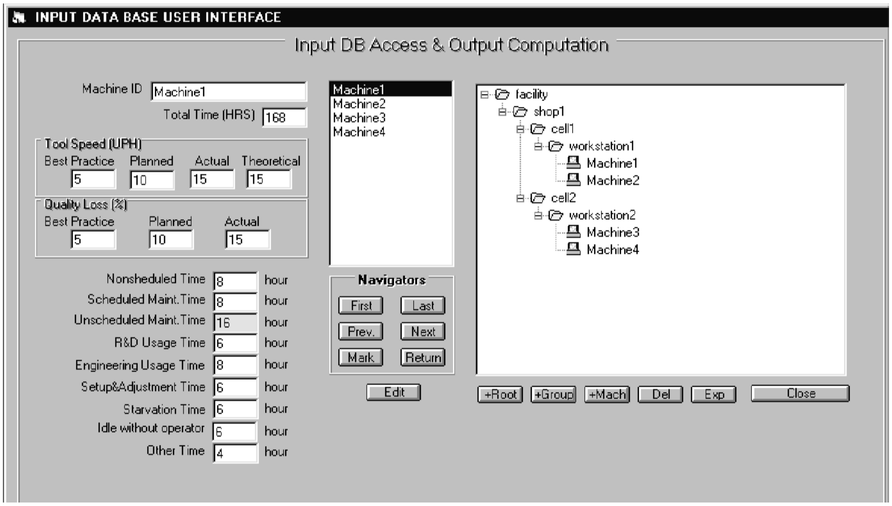
The good achievable units in equation (10) show the number of good units achievable during the actual production time.

$$\begin{aligned}&\text{Good achievable units} = \text{actual production time} \times \text{current tool speed} \times \\ &(1 - \text{current quality loss})\end{aligned} \tag{10}$$

To compute OEE, throughput, and cost during the time loss, we developed a prototype system, referred to as the total productivity improvement visibility system (TPIS). One feature in TPIS is the simultaneous comparison function for multiple equipment through the groups. TPIS supports two types of groups: the operation/maintenance groups and the analysis groups. An operation/maintenance group refers to a hierarchy of facilities, shops, cells, workstations, and equipment (Askin and Standridge, 1993). The instance of a higher level consists of one or more instances of lower levels. For example, a facility may consist of five shops, and each shop may be composed of multiple cells. Within this hierarchy, all operations and maintenance activities are performed and controlled. In other words, an operation/maintenance group represents a physical layout of the machines in the system. However, system analysts are sometimes interested in analyzing several machines across the instances of the operation/maintenance groups. Thus, they may create some groups for analysis purposes. These groups are called analysis groups. Hence, an analysis group is logical. All machines within these two types of groups can be evaluated and compared according to multiple criteria in the TPIS environment.

Numerical example through TPIS

The features of TPIS can be best explained using a simple example. Some input data in this example were obtained from Giegling *et al.* (1997) and Konopka and Trybula (1996). Figure 4 shows an operation/maintenance group consisting of one facility, one shop, two cells, and two workstations. Each workstation contains two machines. The information provided in Figure 4 is stored in an open database connectivity (ODBC) data source. Note that best practice,



Machine ID: Machine1
Total Time (HRS): 168

Tool Speed (UPH)

Best Practice	Planned	Actual	Theoretical
5	10	15	15

Quality Loss (%)

Best Practice	Planned	Actual
5	10	15

Nonsheduled Time: 8 hour
Scheduled Maint.Time: 8 hour
Unscheduled Maint.Time: 16 hour
R&D Usage Time: 6 hour
Engineering Usage Time: 8 hour
Setup&Adjustment Time: 6 hour
Starvation Time: 6 hour
Idle without operator: 6 hour
Other Time: 4 hour

Figure 4.
Data input screen

planned, actual and theoretical tool speed and quality loss are captured. For quality loss, the theoretical value must be zero.

Based on this information, TPIS performs state analysis, lost unit analysis, relative loss analysis, OEE 1 analysis and OEE 2 analysis for a single machine. The state analysis shows the percent losses of the time in each equipment state. The lost unit analysis computes the unit of product lost during the time losses. The relative loss analysis classifies losses into planned, cause and effect, and quality loss where the planned represents the planned losses and cause and effect denotes the unplanned losses. The analysis also shows the relative size of loss at each classification. The procedure for determining how the total time is reduced into valuable production time is graphically shown for this analysis in Figure 5.

Consider machine 1 in workstation 1. The results of OEE 1 analysis and the lost unit analysis for the machine 1 are represented in Figures 6 and 7, respectively. In Figure 6, the OEE for the machine 1 is 37.70 (percent) using the planned tool speed and best practice quality loss.

In Figure 7, for lost unit analysis, the total units and good unit are calculated using equations (4) and (5), respectively. The total production summary is computed using equations (6), (7) and (8). The actual production summary is computed using the actual production time computed in Figure 6. The possible is determined by multiplying the actual production time with the best practice tool speed, which results in 500 units.

For multiple equipment comparisons, once either an operation/maintenance group or an analyst-made analysis group is selected, TPIS supports four analyses: state analysis, output analysis, OEE 1 analysis and OEE 2 analysis. The results of these analyses can be graphically displayed. The output analysis calculates the throughput for all equipment for all time losses. Figure 8 shows the results of OEE 1 analyses for all machines. Figure 9 is the graphical

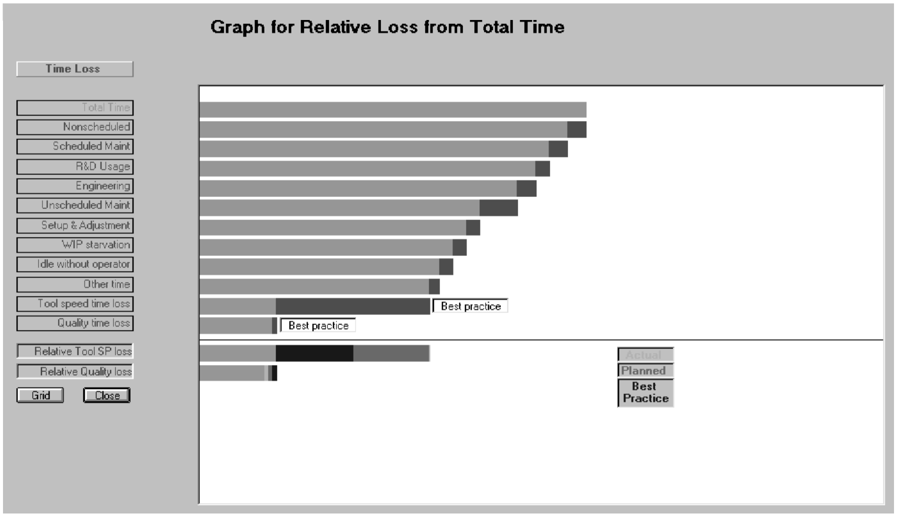
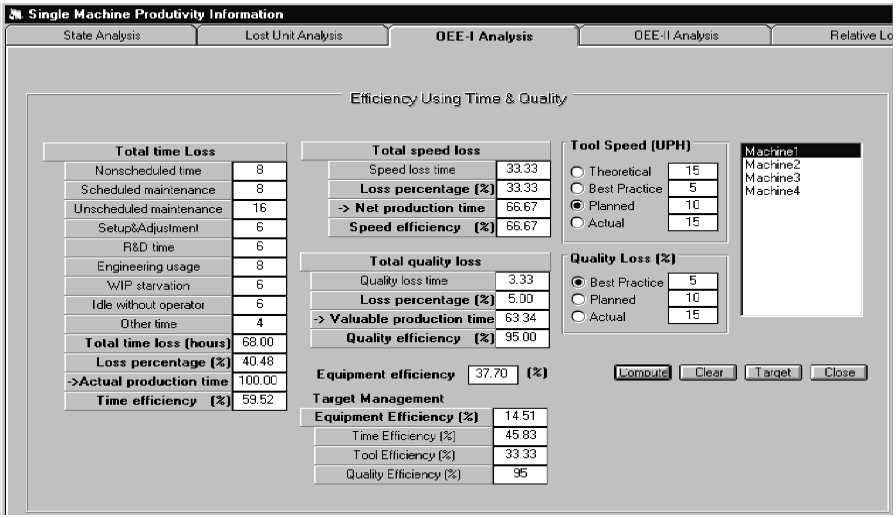


Figure 5.
Graph of relative losses for machine 1



Efficiency Using Time & Quality

Total time Loss	
Nonscheduled time	8
Scheduled maintenance	8
Unscheduled maintenance	16
Setup&Adjustment	6
R&D time	6
Engineering usage	8
WIP starvation	6
Idle without operator	6
Other time	4
Total time loss (hours)	68.00
Loss percentage (%)	40.48
->Actual production time	100.00
Time efficiency (%)	59.52

Total speed loss	
Speed loss time	33.33
Loss percentage (%)	33.33
-> Net production time	66.67
Speed efficiency (%)	66.67

Total quality loss	
Quality loss time	3.33
Loss percentage (%)	5.00
-> Valuable production time	63.34
Quality efficiency (%)	95.00

Equipment efficiency 37.70 **(%)**

Target Management

Equipment Efficiency (%)	14.51
Time Efficiency (%)	45.83
Tool Efficiency (%)	33.33
Quality Efficiency (%)	95

Tool Speed (UPH)

○ Theoretical	15
○ Best Practice	5
● Planned	10
○ Actual	15

Quality Loss (%)

● Best Practice	5
○ Planned	10
○ Actual	15

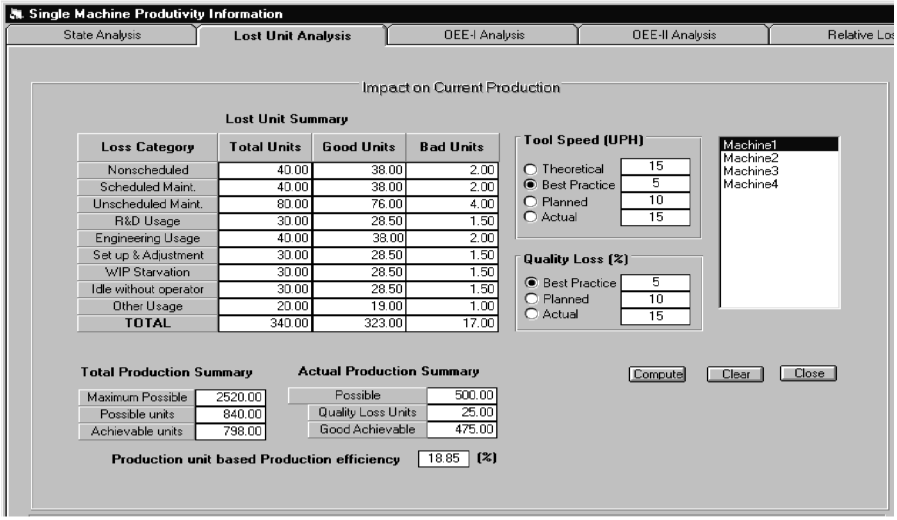
Machine1
Machine2
Machine3
Machine4

Figure 6.
OEE 1 analysis for machine 1

representation of the results obtained in Figure 8. Managers may sometimes want to set a target value for each performance measure and compare the target value with the current value. When the difference between the target and current value is beyond the tolerance limit, the activities for searching the hidden losses may be initiated.

Beyond OEE

Once losses are analyzed from the accurate data, the next step is to attempt to reduce those losses. TPM emphasizes the role of autonomous maintenance by operators and small group activities for loss elimination. However, to



Impact on Current Production

Lost Unit Summary

Loss Category	Total Units	Good Units	Bad Units
Nonscheduled	40.00	38.00	2.00
Scheduled Maint.	40.00	38.00	2.00
Unscheduled Maint.	80.00	76.00	4.00
R&D Usage	30.00	28.50	1.50
Engineering Usage	40.00	38.00	2.00
Set up & Adjustment	30.00	28.50	1.50
WIP Starvation	30.00	28.50	1.50
Idle without operator	30.00	28.50	1.50
Other Usage	20.00	19.00	1.00
TOTAL	340.00	323.00	17.00

Tool Speed (UPH)

○ Theoretical	15
● Best Practice	5
○ Planned	10
○ Actual	15

Quality Loss (%)

● Best Practice	5
○ Planned	10
○ Actual	15

Machine1
Machine2
Machine3
Machine4

Total Production Summary

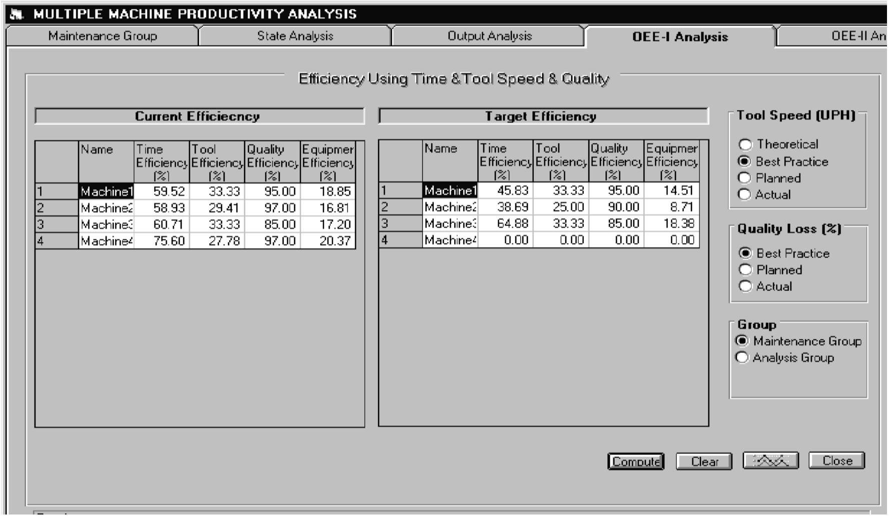
Maximum Possible	2520.00
Possible units	840.00
Achievable units	798.00

Actual Production Summary

Possible	500.00
Quality Loss Units	25.00
Good Achievable	475.00

Production unit based Production efficiency 18.85 **(%)**

Figure 7.
Lost unit analysis for machine 1



Efficiency Using Time &Tool Speed & Quality

Current Efficiecncy

	Name	Time Efficiency (%)	Tool Efficiency (%)	Quality Efficiency (%)	Equipmer Efficiency (%)
1	Machine1	59.52	33.33	95.00	18.85
2	Machine2	58.93	29.41	97.00	16.81
3	Machine3	60.71	33.33	85.00	17.20
4	Machine4	75.60	27.78	97.00	20.37

Target Efficiency

	Name	Time Efficiency (%)	Tool Efficiency (%)	Quality Efficiency (%)	Equipmer Efficiency (%)
1	Machine1	45.83	33.33	95.00	14.51
2	Machine2	38.69	25.00	90.00	8.71
3	Machine3	64.88	33.33	85.00	18.38
4	Machine4	0.00	0.00	0.00	0.00

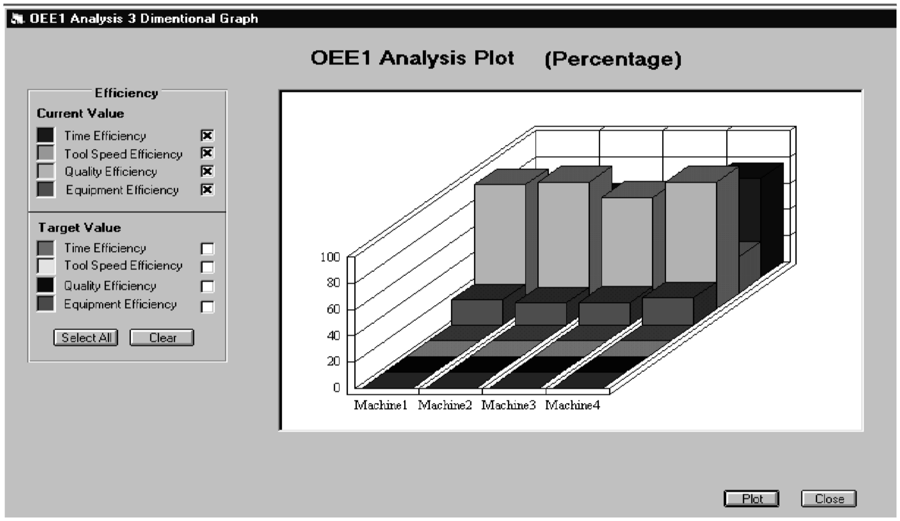
Tool Speed (UPH)
○ Theoretical
● Best Practice
○ Planned
○ Actual

Quality Loss (%)
● Best Practice
○ Planned
○ Actual

Group
● Maintenance Group
○ Analysis Group

Figure 8.
OEE 1 for facility group

successfully perform these maintenance and group activities, managers should provide clear tools and methods. It is believed that no definite single tool or method can eliminate all losses. However, understanding the characteristics of the losses may increase the chance of finding the causes for those losses. For example, nonscheduled time, scheduled maintenance time, R&D time, and engineering time are planned times. Hence, those time losses can be controlled by management policy. However, unscheduled maintenance time, setup and adjustment time, WIP starvation time, and idle time without operators are difficult to control as they are the functions of several interrelated factors. The unscheduled maintenance time has trade-off relations with the scheduled



Efficiency

Current Value

- Time Efficiency ☒
- Tool Speed Efficiency ☒
- Quality Efficiency ☒
- Equipment Efficiency ☒

Target Value

- Time Efficiency ☐
- Tool Speed Efficiency ☐
- Quality Efficiency ☐
- Equipment Efficiency ☐

Figure 9. Graphical representation of OEE 1 for facility

maintenance time. Thus, the optimal preventive maintenance schedule must consider both scheduled and unscheduled maintenance time together. Setup and adjustment time and WIP starvation time have a relation with the scheduling and dispatching policy. As stated earlier, WIP starvation time can be increased by the difference in the production capacity between predecessor and successor process. Hence, it is important to maintain the production capacity balancing between them. Maintaining proper number of WIP in the process can also reduce it since whenever the WIP starvation occurs at the specific equipment, the existing WIP can be loaded to the equipment. Idle time without operator can take place by man-machine assignment scheme, hence this loss may be reduced by solving the man-machine interference problem (Stecke and Aronson, 1985). Loss time due to tool speed may occur due to technical problems. To successfully eliminate losses, we encourage efforts based on the process improvement. It is also helpful to understand the relative importance of the equipment. For example, equipment on bottleneck must have more priority than equipment on non-bottleneck. According to the Theory of Constraints (TOC), the equipment on bottleneck should be first identified because the loss elimination in non-bottleneck equipment increases the idle time (Rose *et al.*, 1995).

Summary and conclusions

In this paper we proposed a loss classification scheme based on the SEMI E10-92 for capital-intensive industry and provided justification for this scheme. We also presented the methodology for designing the necessary data collection system – a system that can serve as a template for any industry. To assist decision makers, we developed the TPIS to implement our proposed OEE and other analyses, which allow for the comparison of multiple equipment.

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