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Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion

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The quest for improving productivity in the current global competitive environment has led to a need for rigorously defined performance-measurement systems for manufacturing processes. In this paper, overall equipment effectiveness (OEE) is described as one such performance-measurement tool that measures different types of production losses and indicates areas of process improvement. Analysis is done on how OEE has evolved leading to other tools like total equipment effectiveness performance, production equipment effectiveness, overall factory effectiveness, overall plant effectiveness, and overall asset effectiveness. Two industrial examples of OEE application are discussed, and the differences between theory and practice analysed. Finally, a framework for classifying and measuring production losses for overall production effectiveness is proposed. The framework harmonizes the differences between theory and practice and makes possible the presentation of overall production/asset effectiveness that can be customized with the manufacturers needs to improve productivity.

Keywords: Performance measurement; Overall equipment effectiveness; Manufacturing

1. Introduction

The evolution towards a global economy has expanded the base of competition for virtually all businesses. By the very nature of the word competition, it is implied that someone out there is always keeping score. The tally on the scorecard may be a measure of more sales, increased profit or a growing customer base. Regardless of the criteria of measurement used, to remain competitive, you have to put up more points on the board. In order to beat competition, there is a basic business demand to get better at what is done and at meeting customers' expectations.

As noted by Fleischer *et al*. (2006), the competitiveness of manufacturing companies depends on the availability and productivity of their production facilities. Huang *et al*. (2003) also state that due to intense global competition, companies are striving to improve and optimize their productivity in order to remain competitive. This would be possible if the production losses were identified and eliminated so that the manufacturers could bring their products to the market at a minimum cost.

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This situation has led to a need for a rigorously defined performance measurement system that is able to take into account different important elements of productivity in a manufacturing process.

The total productive maintenance (TPM) concept, launched by Nakajima (1988) in the 1980s, provided a quantitive metric called overall equipment effectiveness (OEE) for measuring productivity of individual equipment in a factory. It identifies and measures losses of important aspects of manufacturing namely availability, performance, and quality rate. This supports the improvement of equipment effectiveness and thereby its productivity. The OEE concept is becoming increasingly popular and has been widely used as a quantitative tool essential for measurement of productivity especially in semiconductor-manufacture operations (Huang *et al.* 2003). Manufacturers in other industries have also embraced it to improve their asset utilization.

The industrial application of OEE, as it is today, varies from one industry to another. Though the basis of measuring effectiveness is derived from the original OEE concept, manufacturers have customized OEE to fit their particular industrial requirements. Furthermore, the term OEE has been modified in literature to different other terms with regard to the concept of application. This has led to broadening of OEE to overall factory effectiveness (OFE), overall plant effectiveness (OPE), overall throughput effectiveness (OTE), production equipment effectiveness (PEE), overall asset effectiveness (OAE), and total equipment effectiveness performance (TEEP).

The objective of this paper is to investigate how the OEE tool has evolved with time and how it has been applied to fit the individual needs of the industries. Two industrial examples are analysed to show how the OEE concept is applied to enhance productivity in industries and the different types of production losses measured. To harmonize the different OEE concepts in literature and practice, a general framework with different categories of production losses has been developed. This framework gives different categories of losses that are important in measuring overall production effectiveness. Finally, this paper discusses the benefits and challenges of using the OEE measurement tool and the type of processes where its benefits are significant.

2. OEE measurement tool: overview

The OEE measurement tool was developed from the TPM concept launched by Nakajima (1988). The goal of TPM is to achieve zero breakdown and zero defects related to equipment. The consequence of reducing breakdowns and defects is improvements in production rate, reductions in costs, reductions in inventory, and eventually increases in labour productivity. The TPM concept puts much attention on production equipments, since they have a high influence on quality, productivity, cost, inventory, safety and health, and production output. This is especially true for highly automated processes.

OEE is defined as a measure of total equipment performance, that is, the degree to which the equipment is doing what it is supposed to do (Williamson 2006). It is a three-part analysis tool for equipment performance based on its availability, performance, and quality rate of the output. It is used to identify for an equipment the related losses for the purpose of improving total asset performance and reliability. It categorizes major losses or reasons for poor performance and therefore provides the basis for setting improvement priorities and beginning of root cause analysis. It can point to hidden capacity in a manufacturing process and lead to balanced flow. OEE is used to track and trace improvements or decline in equipment effectiveness over a period of time (Bulent *et al*. 2000).

Confusion exists as to whether OEE indeed measures effectiviness (as depicted by its name) or whether it is an efficiency measure. In the literature (US Department of Energy 1995), effectiveness is defined as a process characteristic that indicates the degree to which the process output conforms to the requirements. It indicates whether things are done correctly. Efficiency, on the other hand, is defined as a process characteristic indicating the degree to which the process produces the required output at minimum resource cost. It indicates whether things are done correctly. The three measures (availability rate, performance rate, and quality rate) captured by the OEE tool indicates the degree of conformation to output requirements. Therefore, indeed the OEE tool is a measure of effectiveness. This is in agreement with the definition in literature that OEE measures the degree to which the equipment is doing what it is supposed to do, based on availability, performance, and quality rate (Williamson 2006).

The OEE tool is designed to identify losses that reduce the equipment effectiveness. These losses are activities that absorb resources but create no value. According to Jonsson and Lesshammar (1999), the losses are due to manufacturing disturbances that are either chronic or sporadic. Chronic disturbances are small and hidden, and are a result of several concurrent causes. Sporadic disturbances on the other hand are more obvious since they occur quickly and have large deviations from the normal state. It is a bottom-up approach where an integrated workforce strives to achieve overall equipment effectiveness by eliminating six large losses (Nakajima 1988). The six large losses are given below, with some examples from a palletizing plant in a brewery as analysed by Pintelon *et al*. (2000).

Downtime losses:

(1) Breakdown losses categorized as time losses and quantity losses caused by equipment failure or breakdown. For example, a breakdown of palletizing plant motor in a brewery leads to downtime and thus production loss.
(2) Set-up and adjustment losses occur when production is changing over from requirement of one item to another. In a brewery plant, this type of loss is encountered during set-ups between different products, testing during start-ups, and fine tuning of machines and instruments.

Speed losses:

(3) Idling and minor stoppage losses occur when production is interrupted by temporary malfunction or when a machine is idling. For example, dirty photocells on palletizing machines cause minor stoppages. Though they are quickly fixed, much capacity is lost due to their frequency.
(4) Reduced speed losses refer to the difference between equipment design speed and actual operating speed. In a palletizing plant, the use of unadapted pallets leads to longer processing times for the same number of bottles leading to speed losses.

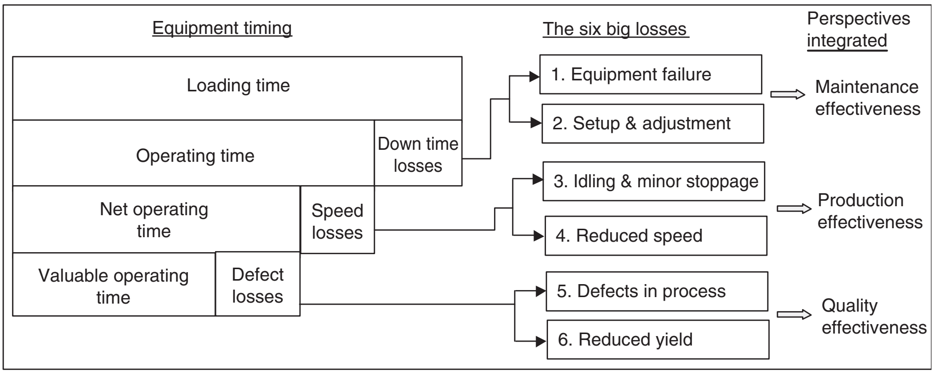

Figure 1. OEE measurement tool and the perspectives of performance integrated in the tool.

Quality losses:

(5) Quality defects and rework are losses in quality caused by malfunctioning production equipment. For example, some pallet types get stuck in between depalletizer and unpacker and are damaged.
(6) Reduced yield during start-up are yield losses that occur from machine start-up to stabilization. For example, in the brewery, poor preparation for morning shift by night shift leads to problems with the filling taps and thus leads to reduced yields.

The six large losses are measured by OEE, which is a function of availability (A), performance (P) and quality rate (Q). Therefore:

$$\text{OEE} = A \times P \times Q,$$

where:

$$\text{Availability rate } (A) = \frac{\text{Operating time } (h)}{\text{Loading time } (h)} \times 100$$

$$\text{Operating time} = \text{Loading time} - \text{Down time}$$

$$\text{Performance efficiency } (P) = \frac{\text{Theoretical cycle time } (h) \times \text{Actual output (units)}}{\text{Operating time } (h)}$$

$$\text{Quality rate } (Q) = \frac{\text{Total production} - \text{Defect amount}}{\text{Total production (units)}} \times 100.$$

The OEE measurement tool has its strength in the way it integrates different important aspects of manufacturing into a single measurement tool. The perspectives integrated in the OEE tool are the maintenance effectiveness, production efficiency, and quality efficiency, as shown in figure 1.

3. Evolution of OEE

Though the OEE tool has become increasingly popular and has been widely used as a quantitative tool essential for measurement of productivity, it is only limited to productivity behaviour of individual equipments (Huang *et al.* 2003). Scott and Pisa (1998) have pointed out that the gains in OEE, while important and ongoing, are insufficient because no machine is isolated. They indicate that the manufacturing process is a complex web of interactions among process tools, materials, machines, people, departments, companies, and processes. However, too often, these interdependent activities are viewed in isolation, and there is a lack of coordination in deploying available factory resources (people, information materials, and tools) to manage work efficiently. It is therefore necessary to focus one's attention beyond the performance of individual equipment toward performance of the whole factory. The ultimate objective of any factory is to have a highly efficient integrated system and not brilliant individual equipment (Oechsner *et al.* 2003).

This insufficiency of OEE tool has led to modification and enlargement of the original OEE tool to fit a broader perspective as deemed important in the manufacturing systems. With the modification of OEE, different terminologies have also come up in the literature and in practice, coupled with their modified formulations. Some of the modified formulations are limited to effectiveness at the equipment level (e.g. PEE and TEEP), while others have been extended to factory-level effectiveness (e.g. OFE, OTE, OPE, and OAE). This paper looks into these different terminologies and formulations developed in the literature. Further, two industrial examples are discussed as an illustration of industrial practice concerning OEE. This has been done using examples from two Western European companies. The different terminologies and consequent formulations are as follows.

3.1 *TEEP*

TEEP, proposed by Ivancic (1998), is very similar to OEE. The main difference lies in the inclusion of planned downtime in the total planned time horizon. In order to show clearly how maintenance contributes to the bottom line productivity of the plant, a clear distinction is made between planned downtime and unplanned downtime. Minimizing unplanned shutdown, sometimes called technical downtime, is a common goal in maintenance. Unplanned downtime is a function of the number of breakdowns within a specified time period and related measures such as mean time between failures (MTBF) and mean time to repair (MTTR) (Pintelon *et al.* 2000). MTBF and MTTR are claimed to be measures of equipment achievement and are related to objectives such as functional performance and process capability (Wilson 1999).

With the help of TEEP, planned and unplanned downtime can be measured. Thorough analysis of these two elements enables the maintenance function to improve equipments availability by either increasing the MTBF or reducing the MTTR. The other elements included in the TEEP measure are the speed losses and quality rate, which are also in OEE. The TEEP is calculated by dividing the valuable operating time (VOT) with the total available time (T_T) as shown in figure 2. The constituent elements (losses) in TEEP are analysed and measured as shown in figure 3.

The TEEP measure, like OEE, is limited to equipment-level productivity. It is also applicable to a processing plant or a flow shop where the production process can be treated like a single production entity.

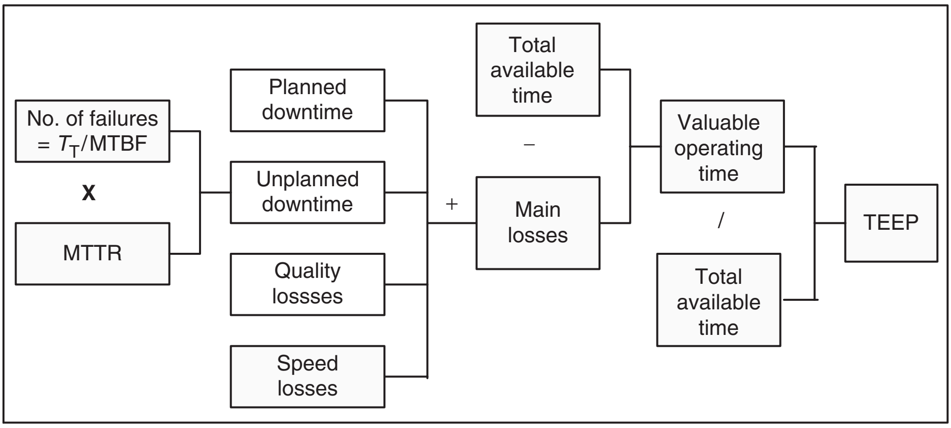

Figure 2. Constituent elements used in the calculation of TEEP.

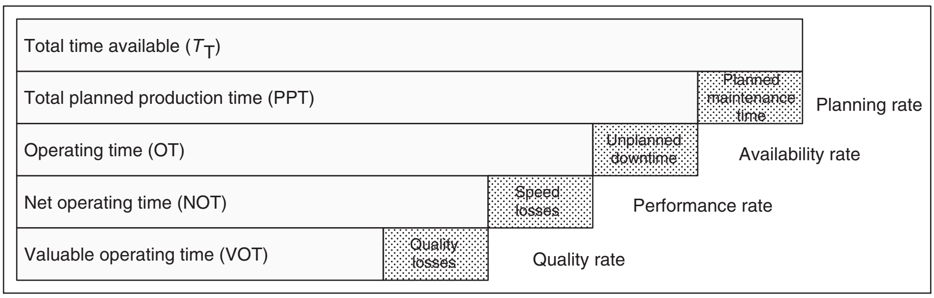

Figure 3. TEEP diagram and its constituent elements.

3.2 *PEE*

PEE, formulated by Raouf (1994), is similar to OEE. The main difference with OEE is the allocation of weights to the various items in the overall effectiveness. It assumes that quality has a different weight from performance and different to availability contrary to the basic assumption in OEE that the three elements have the same weight. It also makes a distinction between two different types of production operations, namely:

(1) discrete-type production operations; and
(2) continuous process operation.

For discrete-type production operation, PEE is calculated as follows:

$$\text{PEE} = (A^{\mathcal{K}1})(E^{\mathcal{K}2})(Q^{\mathcal{K}3}),$$

where A = availability; E = performance efficiency; Q = quality efficiency. κ_i is the weights of the PEE elements (for i = 1–3), $0 < \kappa_i \leq 1$ and $\kappa_i = 1$.

For continuous process operation, PEE is defined as function of availability (A_1), attainment (A_2), performance efficiency (E), quality rates (Q), product support

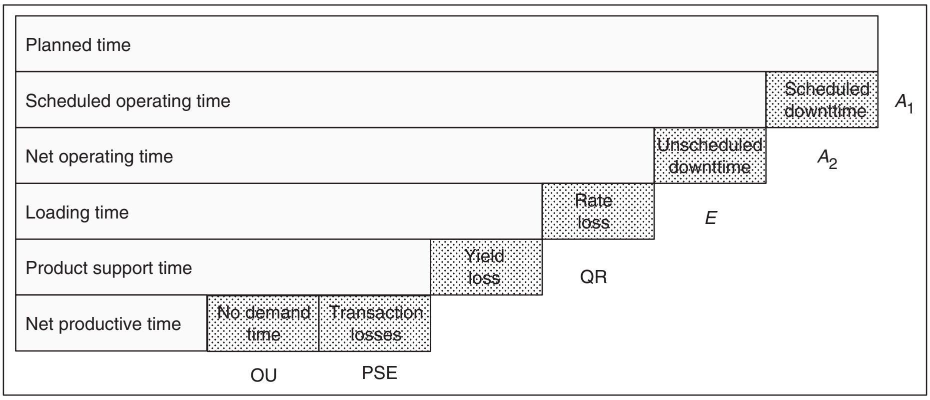

Figure 4. General outline of PEE diagram for continuous process.

efficiency (PSE), and operating utility (OU). These losses are outlined in PEE diagram as shown in figure 4. Therefore:

$$\text{PEE} = (A_1)^{\mathcal{K}1}(A_2)^{\kappa 2}(E^{\kappa 3})(Q^{\kappa 4})(\text{PSE})^{\kappa 5}(\text{OU})^{\kappa 6},$$

where κ_i is the weight of the PEE elements (for $i = 1 - 6$), $0 < \kappa_i \leq 1$ and $\sum \kappa_i = 1$.

The availability rate considers the planned or scheduled downtime and is similar to the planning rate in TEEP. The attainment rate considers the unscheduled downtime and is similar to availability in TEEP. The other additional factors included are the product support efficiency and operating utility, which considers the transaction losses and no demand time, respectively. It is assumed that there is no setup time needed for the continuous process operation, and therefore setup time loss has not been included in the PEE diagram.

3.3 *OFE*

The OFE was developed to measure the factory-level effectiveness, where several production steps or machines are installed to form a production process. While OEE is about achieving excellence in individual equipment, OFE is about the relationships among different machines and processes. As noted by Scott and Pisa (1998), OFE seeks to integrate the many activities and information systems that the production process entails. OFE is therefore a term about combining activities, relationships between different machines and processes, integrating information, decisions, and actions across many independent systems and subsystems (Oechsner *et al*. 2003). Among the issues that OFE seeks to accomplish are: to synchronize the production schedule with planned downtime, setup time and qualification time through a tighter connectivity to enterprise planning systems and infinite capacity schedule; to optimize the sequence of orders, works or jobs; and to ensure a balanced line and smooth flow of work by integrating micro-scheduling with overall plant scheduling (Williamson 2006).

Until now, there was no common approach for the OFE metrics. However, several proposals are given in the literature, of which two are discussed here. The approach of Scott and Pisa (1998) considers the fact that different plants have different goals, and so there can be no single indicator. They suggest creating a composite metrics (e.g. cycle-time efficiency, on-time delivery, capacity utilization, rework rate, yield rate, etc.) that ask for specific key goals. The important thing is to define measuring criteria for success and application of weight factors as desired to meet corporate goals. For these metrics, an overall result is computed.

Another approach proposed by Huang *et al*. (2003) considers simulation analysis as the most reliable method in studying the dynamic performance of manufacturing systems. It defines an OFE metric, OTE, developed on the basis of OEE metrics analysis, for complex connected manufacturing systems. These metrics are integrated with simulation analysis for manufacturing productivity improvement.

From the OEE formula and the OEE diagram (figure 1), OEE is calculated in terms of production units as:

$$\mathrm{OEE} = \frac{\text{Number of good parts produced } (P_g)}{\text{Theoretical number of parts produced in total time } (P_{\mathrm{th}})},$$

where

$$P_{\mathrm{th}} = \text{Theoretical production rate } (R_{\mathrm{th}}) \times \text{Total available time } (T_{\mathrm{T}}).$$

By extending the expression of unit-based OEE to factory level, the OTE during period T_{T} is defined as:

$$\mathrm{OTE} = \frac{\text{Good product output (units) from factory } (P_{g(\mathrm{F})})}{\text{Theoretical attainable product output (units) from factory in total time } (P_{\mathrm{F(th)}})}.$$

Similarly:

$$P_{\mathrm{th(F)}} = R_{\mathrm{th(F)}} \cdot T_T,$$

where $R_{\mathrm{th(F)}}$ is the theoretical processing rate for actual product output from factory.

Using these formulations, OFE for any manufacturing system can be calculated. Since many manufacturing systems are in parallel and/or series, the OTE formulation for these two systems has been developed.

It is noted, however, that the OFE metric are in the development stage, and a simulation analysis is considered the most reliable method to date in studying the dynamic performance of manufacturing systems (Huang *et al*. 2003). The underlying concept behind simulation is that manufacturing systems can be treated as a combination of a number of simple subsystems, which in turn are the combination of individual production equipment (Huang 2002). Productivity metrics are then integrated in the model to measure system performance and help identify productivity improvement opportunities.

3.4 *OAE and OPE*

OAE and OPE are measurement tools that have been developed from the OEE tool. Though the terms have limited applications in literature, they have been applied extensively in the industries. They are applied to identify and measure all the losses associated with the overall production process. The two terms have the same meaning with regard to industrial application. However, the elements or losses measured differ from one industry to another. Production losses are measured by measuring either time losses or production output losses.

Two industrial examples of OAE/OPE application are discussed. The two companies are multinationals located in western Europe, and their identities are left anonymous in this paper. For the two industrial examples, a study was done on the structure of their OAE diagram and the type of production losses it measures. However, the study did not involve a detailed case study on the dynamics of data collection.

4. Industrial examples of OAE application

4.1 *Company A*

Company A is a chemical processing company. The OAE tool is used with the objective of maximizing the production output and minimizing losses of all types. The company, therefore, use the production output (tonnage) approach in the OAE tool to identify the losses.

The maximum output that the company is able to produce at optimum capacity is defined as the theoretical maximum tonnage (T_T). This is the maximum production capacity that the plant is able to attain, expressed as a quantity related to time unit: an hour, a day, a week, a month, or a year. The optimum operation of a plant is reduced in several circumstances by production losses (PL). Instead of the anticipated theoretical tonnage T_T, the plant delivers an actual tonnage T_{ACT} corresponding to the tonnage actually produced within the commercial specifications. Therefore,

$$\text{Production losses, PL} = T_T - T_{ACT}$$

The identifiable production losses are grouped in the following categories.

4.1.1 PL_{COM}. These are production losses related to commercial demand and are the result of plant shutdowns, lower production rates, or production overcapacity compared with commercial demand. They also include the quantity of out-of-specification product attributable to adjusted operating rate.

4.1.2 PL_{CH}. The production schedule provides for consecutive production of products with different characteristics. The changeover entails slower production or stoppage to adjust the operating parameters, or swap equipments and tools. The result is a production loss (PL_{CH}) compared with continued operation with the same product. In addition, this situation frequently results in quantities of product that do not meet quality specifications and are also entered under PL_{CH}.

4.1.3 PL_F. These are the production losses resulting from poor reliability. Two different types of poor reliability may occur:

(a) PL_{FE}: These are production losses due to external causes that are totally outside the company's control. This may be due to:
- third-party failure to supply;
- shortage of energy (electricity, gas, etc.);
- supply problems resulting from logistics (e.g. railways, road haulers, sea, or waterway transport);
- exceptional poor weather conditions.

(b) PL_{FI}: These are production losses due to internal causes for which the company is accountable. These production losses result from production slowdowns or stoppages as a result of the following occurrences:
- equipment failure;
- utility shortage;
- labour unrest;
- organization problems;
- safety, health and environmental problems;
- mandatory planned shutdowns;
- operation errors;
- planned shutdown due to capital expenditure work.

4.1.4 PL_{OP}. These are production losses related to poor operation performance. Causes may be due to problems relating to process, equipment performance degradation through aging, or losses associated with shutdown or start-up difficulties (especially after major shutdowns).

4.1.5 PL_Q. These are losses due to quality of the products (failure to produce product within specification). They include all products out of specification due to technical or commercial reasons (except out-of-specification products related to PL_{COM} and PL_{CH}), as well as quantities of recycled product.

The production losses are presented in the OAE diagram as shown in figure 5. From the OAE diagram, OAE and OAU are calculated as follows:

$$\mathrm{OAE} = \frac{T_{\mathrm{ACT}}}{T_{\mathrm{T}}}$$

$$\mathrm{OAU} = \frac{T_{\mathrm{ACT}}}{T_{\mathrm{T}} - PL_{\mathrm{COM}}}.$$

The various categories of production losses, as outlined in the OAE diagram, help to highlight the possible areas where losses can be reduced. From the OAE diagram, the other production loss rates are calculated. The asset effectiveness results are reported on a monthly basis, and from the monthly report, yearly performance can be calculated.

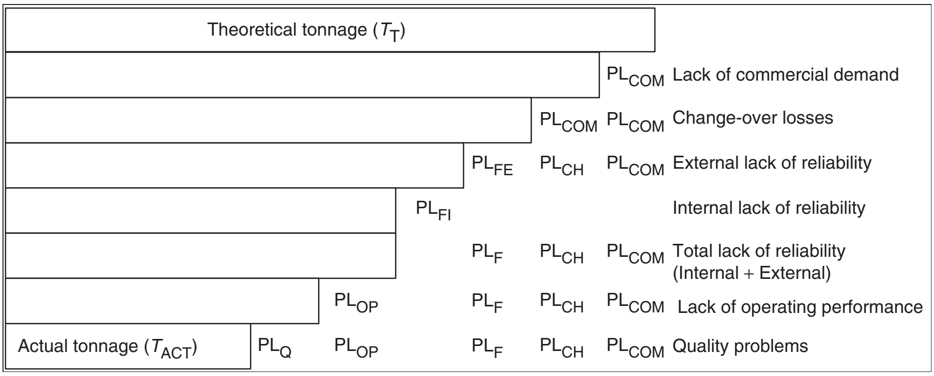

Figure 5. OAE diagram of company A showing the production losses.

4.2 *Company B*

Company B is a packaging industry. OEE metrics are used to identify the major drivers of packaging-line manufacturing performance and identify areas of process improvement. The defined drivers of manufacturing performance are equipment utilization based on availability 24 h per day, capacity utilization, OEE, and OPE.

The manufacturing performance measurement is based on equipment timings, and therefore the losses are measured in terms of time losses. It is assumed that the equipment is available to be run for 24 h per day and 7 days per week. The time usage for the equipment is measured as follows.

4.2.1 Unscheduled time. This is defined as the time for which the equipment is available to run more production. This is the available time due to holidays, midweek idle time, weekends, and reduced rate due to lack of scheduled demand.

4.2.2 Scheduled downtime. This is the time allocated to scheduled activities on the equipment due to planned maintenance or shut downs, meetings, training or breaks, planned cleaning, and standby state.

4.2.3 Seven major losses. Seven major time losses can be encountered during the production process. These are due to:

(1) Major stoppages due to machine failure or due to production defect: the stoppage is said to be major if it takes more than 10 min. Major stoppages may also result from supplier-related downtime or warehouse downtime.
(2) Changeover from one product to another or from product of one size to another.
(3) The cutting blade loss, which is the time lost in replacing routine wear parts.
(4) Startup and shutdown losses occurring after annual shutdown, after holidays or weekend, and after lunch and breaks.

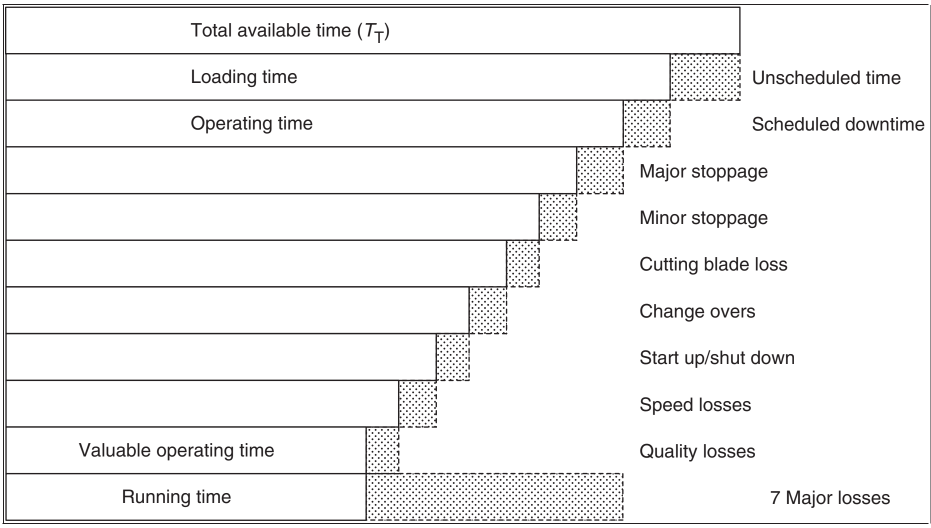

Figure 6. OAE diagram of company B.

(5) Minor stoppages: these are the stoppages that are less than 10 min, for example due to equipment jams.
(6) Speed losses, i.e. the lost equipment capacity resulting from operation at a reduced speed.
(7) Quality losses due to products that fail to meet specifications.

4.2.4 Running time. This is the time that is left for production, and this also refers to valuable operating time. Manufacturing losses are presented in the OAE diagram as shown in figure 6. From the OAE diagram, asset (capacity) utilization, OEE and OPE are calculated.

Asset (capacity) utilization defines how effective an asset is being utilized. The inverse reveals how much more output is available from the current asset if needed today. Thus:

$$\text{Asset utilization} = \frac{\text{Loading time}}{\text{Total available time}}.$$

The OEE measure is defined as the ability to run equipment at the designed speed with zero defects. In order to maximize OEE, the seven major losses should be reduced. Thus:

$$\text{OEE} = \frac{\text{Valuable operating time}}{\text{Operating time}}.$$

Finally, the OPE measures how well the supply chain is effectively utilizing the manufacturing assets. Thus, the OPE measure considers planned downtime and unscheduled time in addition to seven major losses, as supply-chain losses. Thus:

$$\text{OPE} = \frac{\text{Valuable operating time}}{\text{Total available time}}.$$

5. Discussion on the existing tools

The literature review on OEE evolution reveals many differences in formulation of equipments' effectiveness. The main difference lies in the types of production losses that are captured by the measurement tool. Though the original OEE tool identifies six major losses in a production set-up, other types of losses have been found to have a significant contribution to the overall production loss.

In the TEEP tool (figures 2 and 3), considerable emphasis is given to the influence of machine failure and maintenance on plant productivity. Planned downtime is included to show the percentage time and production lost due to shutdown maintenance. Specialized attention is given to unscheduled downtime and related metrics like the MTBF and MTTR. The analysis and improvement of the plant based on these metrics enable the maintenance function to improve the functional performance and process capability of the plant. Like OEE, it also includes losses related to quality and speed. However, the tool only considers losses in the operational level of the plant. It is therefore limited to individual equipment or continuous process effectiveness.

The PEE tool for continuous process (figure 4) also measures the scheduled and unscheduled downtime due to maintenance. However, it goes further and measures losses to due commercial demand and transaction losses. These losses are included to show the percentage of time the machine is down due to a lack of demand. In total, it measures both operational and commercial related losses.

The industrial examples of the OAE application also reveal a large difference in elements included in production-loss identification. For example, in company A, different categories of losses have been defined (figure 5). These include losses related to commercial, internal, and external reasons, changeovers, speed losses, and quality problems. It groups, for example, all internal losses in one category without giving specialized attention to individual causes. This may not be an effective means of measurement because each type of loss requires special attention and corrective action. Company A considers all types of production losses but lacks a clear method of classifying the individual losses, and therefore, the measurements cannot effectively support continuous improvement. Company B, on the other hand, has a complete breakdown of all the operational type of losses (figure 6). It identifies seven major losses which, together with scheduled and unscheduled downtime, constitute all the operational production losses. However, it does not consider production losses due to commercial demand fluctuation or losses due to other internal business or external reasons. These differences lead to the development of an overall production effectiveness framework.

6. In search of a general framework for OAE/OPE measurement

The differences in the measurement of equipment's effectiveness, in literature and practice, leads us to two important and enduring research questions in performance measurement cited by Neely *et al.* (2005):

(1) What needs to be measured?
(2) How will it be measured?

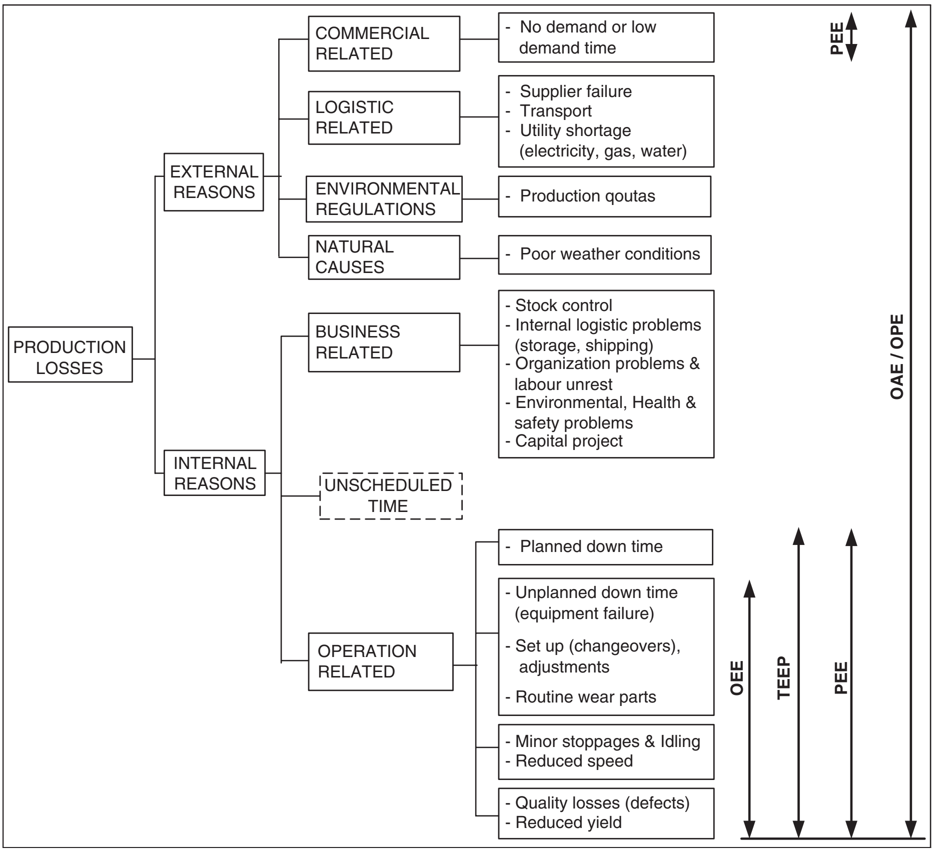

Figure 7. Classification of production losses for calculating overall production effectiveness.

The first question seeks to determine the various factors that influence performance that need to be monitored through a measurement system. The second question includes issues such as the measurement scale being used, the data source, and the frequency of measurement. It is noted in the literature that the way in which these questions are answered can influence the validity, reliability, and practicality of any measure (Thorndike and Hagen 1969).

6.1 *Factors to be measured*

A framework for identifying different types of losses for overall production/asset effectiveness is proposed, as shown in figure 7. The framework classifies production losses into different categories depending on the cause of loss. This classification helps the decision-maker to measure different causes of production losses so that attention can be given to the relevant causes. It also gives a standardized way of measuring asset effectiveness. The following production-loss categories are defined.

6.1.1 Losses due to external reasons. These are production losses caused by factors that are beyond the control of the company and include the following:

(1) Commercial demands: this is the production loss encountered when there is no demand in the market. This may result in plant shutdown or lower production rates.
(2) Logistic problems: these are production losses caused by logistics related problems, and include third-party failure to supply, transport problems resulting in a delay in raw-material arrival and shortage of utilities like electricity, gas, or water.
(3) Environmental regulations: these are losses related production quotas due to environmental degradation. For example, restriction on the amount of carbon dioxide emissions can limit the production quantity. This forces the plant to produce below capacity and therefore amounts to production loss.
(4) Natural causes: these are production losses that result from natural causes like poor weather conditions.

6.1.2 Losses due to internal reasons. These are production losses caused by factors within the control of the company. These causes should be analysed and corrective action taken to minimize the losses. Two major categories of these types of losses are business-related and operation-related losses.

(1) Business-related losses: these are production losses resulting from problems at entire business level. These include:
    - Internal logistics problems like shipping and storage of the finished goods: this may cause production to slow down or shut down for a while. Production can also be slowed to control the amount of finished goods stocks.
    - Organization problems or labour unrest will cause the production to shutdown leading to production loss.
    - Environmental, health and safety problems cause production to be slowed down or stopped.
    - Capital projects within the plant forces production to be stopped until they are finished.
(2) Operation-related losses: these are production losses encountered in the cause of running the plant. They are the most regular problems encountered in production, and therefore they are the most analysed losses. They include the six major losses cited in the literature (Nakajima 1988) and the scheduled downtime. Due to their chronic nature of occurrence, much of the study on equipment effectiveness is directed towards them.

One such operationally related loss is unscheduled downtime due to machine failure. The equipment-failure downtime determines the equipment availability, and this is defined as the period of time for which a machine can actually be used for production purposes. The availability rate is determined by three factors, namely reliability, maintainability, and maintenance readiness (Fleischer *et al.* 2006). The reliability factor is the length of time equipment is able to run without failure and is measured by MTBF. Maintainability is the length of time for which an equipment can be brought back to an operating condition after it has failed, and is measured by MTTR. Since it is the responsibility of maintenance function to ensure the availability of production equipment, the availability rate is related to maintenance effectiveness.

The other important time loss is due to changeovers and replacement of routine wear parts. Though the changeover time varies from one operation to another, it takes a considerable amount of time for analysis and reduction. The other major losses are minor stoppages, idling time, reduced speed, and quality defects that have been discussed in the literature review. Specialized measurement, analysis, and reduction of each of these losses are important in improving the equipment effectiveness.

The inclusion of all these causes of production losses in the OAE calculation gives a complete picture of overall production effectiveness and supports decision-makers in identifying areas where improvement is necessary. The unscheduled time is included to show the unutilized capacity and the available output from the current assets. Clear differences between OEE, TEEP, PEE, and OPE are also shown in figure 7, as well as the type of losses each of them includes.

As shown in figure 7, effectiveness measures can be analysed from equipment level (OEE) and operation level, and at overall production or factory level. OEE is defined as a measure of ability to run equipment without failure, at the designed speed and with zero defects. It is concluded therefore that only the production losses related to equipment should be used to calculate the OEE. Scheduled downtime should therefore not be used in OEE calculation.

6.2 *How to measure OEE*

This is an important aspect that addresses the measurement scale, data source, and measurement frequency. The validity and usefulness of OEE measure are highly dependent on the data collection and accuracy. Data collection is an important phase of performance measurement and continuous improvement, since what has not been measured cannot be improved. It has been claimed that many manufacturing companies measure the efficiency of their lines in such a way as to 'mask' many of the causes of lost efficiency (Parsec Automation Corp 2005). This is due to inadequate data collection or inaccuracy in data recording. Data collection and accuracy are large challenges for many companies. It is reported in the literature (Ericsson 1997) that accurate equipment performance data are essential to the success and long-term effectiveness of TPM activities. If the extents of equipment failures and production losses are not entirely understood and measured, then TPM actions cannot be deployed optimally to solve major problems or arrest deteriorating performance.

Jonsson and Lesshammar (1999) propose that data collection should be at such a detailed level that fulfils its objective without being unnecessarily demanding of resources. The difficulty of data collection is dependent on the complexity of the manufacturing system and whether the data collection is manual or automated. For manual data collection, the accuracy is very low, since recording of some minor stoppages or downtime can often be forgotten. Though the cost of manual data collection is minimal, detailed manual data collection may demotivate personnel and lead to a reaction against the measurements. With the use of a manufacturing execution system (MES) and enterprise resource planning (ERP), collection of OEE related data is automated in some manufacturing enterprises. Though the cost associated with these installations is considerable, the data accuracy is high, and the data-collection process is simplified. Introduction of these modern software tools has been leveraged to produce sophisticated real-time reports that allow manufacturers to fully understand all their sources of lost productivity (Parsec Automation Corp 2005). With the adoption of this new automated technology of data capture, the areas of lost production time will be easily identified.

To measure production losses using OEE, two units can be used: production output (tonnage) loss and production time loss. Quality and speed losses are calculated using production output while availability is calculated using downtime. Recording of individual production time loss is the most practical measurement method in many production systems. The frequency of measurement varies from one industry to another. For automated data collection, OEE values can be calculated in real time. The values can then be summarized on an hourly and daily basis. For manual data collection, losses (production time and rejects) should be recorded in real time. Then, OEE values can be summarized on a daily basis. From the daily values, weekly and monthly values can be calculated. A current survey on manufacturing companies (Aberdeen Group 2006) indicates that best performing companies are not only more vigilant and persistent in their measurement efforts but also monitor and measure their performance more frequently. The survey indicates that operational measures such as OEE, in such companies is monitored daily in order to indicate corrective or preventive action.

7. Conclusion

From the analysis of the OEE tool, its evolution and application in the industries, it is concluded that OEE is a valuable measure that provides information on the sources of lost time and lost production. Many companies routinely hit capacity constraints and immediately consider adding overtime for existing workers, hiring workers for new shifts, or buying new production line to boost their production capacity. For such companies, the OEE tool can help them to optimize the performance of the existing capacity. OEE is a valuable tool that can help management to unleash hidden capacity and therefore reduce overtime expenditures and allow deferral of major capital investment. It helps to reduce process variability, reducing changeover times and improving operator performance. These are measurable benefits that substantially improve the bottom line of production operation and enhance the companies' competitive edge.

It is shown that OEE has evolved to include other production losses that were not originally included. This has led to the development of new terminologies like TEEP, PEE, OPE, OAE, and OFE. The difference between these terminologies or tools is based on the type of production losses included as shown in figure 7. It was also found that the industrial application of OAE varies from one factory to another. This is dependent on the types of production losses important to each company. From industrial examples analysed, it was found that specialized attention of important losses was lacking. In some cases, some important types of losses were completely left out.

To harmonize the differences in literature and in practice, a framework for measuring the production losses has been developed. This framework proposes three levels of effectiveness measurement, namely equipment-level effectiveness (based on original OEE), operational-level effectiveness (based on TEEP), and business-level effectiveness (OAE/OPE). Due to the chronic nature of the operational causes of production losses, pertinent rates like availability, performance rate, quality rate, scheduled downtime rate, etc. need to be highlighted to enable specialized attention to the particular losses. The framework also identifies losses due to business-related problems like stock control, storage or shipping problems, and other non-operationally related causes. It proposes the measurement of production losses due to external reasons. This may be due to a lack of demand, logistics problems (e.g. supplier or transport failure, utility shortage), environmental regulations, or natural causes. The framework leaves room for customization with respect to losses that need specialized attention. The inclusion of all types of losses in the OAE tool gives management complete information for well-informed decision-making.

It is also concluded that the OAE tool is best suited for the measurement of individual equipment, discrete-type processes, and continuous process effectiveness. This is beneficial in high-volume process-based manufacture where capacity utilization is of a high priority, and stoppages or disruptions are expensive in terms of lost capacity (Bulent *et al*. 2000). However, deployment of OEE in low-volume job shops and some batch processes is not very beneficial. Due to the nature of these processes, the unscheduled production time is high, and thus planned maintenance can take place then. Also, failure of one machine does not have a great impact because production can be rerouted to another machine. The changeover time is not relevant since set-up can be done on one machine as production can be continued on the other. For production processes with buffers in between, OEE would need to be redefined, since downtime on one process stage does not directly affect the next stage.

Finally, the accuracy of the OEE data is very important. The use of OEE as a production measure necessitates accuracy in the performance data collected. Without accurate data, the OEE measure can easily lead to a lack of credibility. It is therefore important to invest time and money to improve data collection. Data collection can also be greatly improved by embracing new automated technology for data collection.

8. Elements of further research

The performance elements measured by the OEE tool, though important, are not sufficient to describe the effectiveness of a product system. Some important measures (e.g. cost and flexibility) are not measured in the OEE. Further research should explore the dynamics of translating equipment effectiveness or loss of effectiveness in terms of cost. Though this possibility is on a case-to-case basis, the cost translation of OEE will have more significance to management. Due to the importance of data accuracy in OEE calculations, further research should include costs and benefits of investing in automated data-collection methods.

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