Alternative approaches for OEE evaluation: some guidelines directing the choice

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Abstract: The Overall Equipment Effectiveness (OEE) is a useful tool for evaluating the time that manufacturing resources spend on adding value operations and for idle or waste time, whose elimination or at least whose reduction is progressively recommended. In this paper, four alternative approaches for OEE evaluation are reviewed and commented on in order to guide practitioners in the choice preceding their adoption. Specifically, in accordance with data required for the computation and results assured by the implementation, a preferable operating field is suggested.

Keywords: lead time, losses, Overall Equipment Effectiveness (OEE)

1. Introduction

During the early production processes design step or the subsequent analysis of existing systems, the issue of limiting the idle and/or waste operating time of manufacturing resources should be pursued, in order to implement systems that promptly respond to customers and assure low costs to companies (Sohlenius 1992).

Overall Equipment Effectiveness (OEE) is a tool available for monitoring how manufacturing resources’ time is spent, which margins are available for improvement and consequently when and with what results corrective actions are executed. Specifically, OEE is usually computed in an initial operative condition and subsequently monitored at regular time intervals, in order to evaluate the existence of continuous improvement, implemented and consolidated year by year, as suggested by the Total Quality Management (TQM) approach.

Furthermore, OEE is particularly useful when the production of new items is carried out by means of existing resources, whose operative conditions are preferably modified as little as possible. As described in Gamberini et al. (2006, 2008, 2009), changing the operative conditions of manufacturing resources induces costs, related to e.g. acquisition of lacking knowledge, execution of new working procedures, execution of new maintenance operations, setting of new workstations. Hence, OEE is an available tool for evaluating the future performance of manufacturing resources and comparing them with the initial situation by considering alternative operative scenarios. In particular, processes with high standards of quality and throughput are addressed (De Groote 1995).


The published papers are focused on three different topics: first describing OEE and its three factors (availability, performance and quality rate) using different definitions proposed by authors; second computing OEE in real life case studies; third the extensions of the OEE index. Specifically, as concerns the first group of published works, an interesting role is covered by authors commenting criticalities emerging when OEE is implemented, i.e. Jonsson and Lesshammar (1999) state difficulties in determining the reference optimum production speed and in differing minor stoppages from short downtime stoppages. Gouvêa Da Costa and Pinheiro De Lima (2002) underline difficulties arising from evaluating the ideal machine cycle time (technical vs planned). Eldridge et al. (2005) cite inconsistencies which have emerged year by year in calculating OEE, specifically in the field of planned downtime losses, minor stoppages classification and machine cycle time. Otherwise, as concerns the third group of published works, interesting contributions are presented, i.e., by Sherwin (2000) that proposes Overall Process Effectiveness to measure the performance of whole processes, Oechsner et al. (2003) that propose a metric for the evaluation of effectiveness of an entire factory, Nachiappan and Anantharam (2006) that define Overall Line Effectiveness to analyse a continuous production line, Garza-Reyes et al. (2008) that develop Overall Resource Effectiveness which considers material efficiency, too and Braglia et al. (2008) that present Overall Equipment Effectiveness of a manufacturing line.

In this paper four alternative approaches for OEE computation are analysed. Specifically, the contributions of Nakajima (1988, 1989), Ames et al. (1995), De Ron and Roooda (2005), Wauters and Mathot (2007) are studied and guidelines for practitioners are given. In particular, guidelines for choosing the most appropriate OEE computation approach in accordance with features of manufacturing systems, data required and assured results are outlined. The aim is to support practitioners in the step preceding OEE implementation. As a consequence, in the section where aforementioned formulations are presented as similar notation as possible is used, in order to highlight similarities and differences among them.

The paper is organized as follows. In section 2 notation is reported. In section 3 a classification of manufacturing
processes, useful for the following part of the paper, is included. In section 4 the four OEE evaluation approaches, focus of the paper, are described. In section 5 a discussion of application fields is reported. In section 6 some conclusions are outlined.

2. Notation

\[ 
\begin{align*}
A & \quad \text{Availability} \\
ACT & \quad \text{Actual cycle time} \\
D_l & \quad \text{Downtime losses} \\
E & \quad \text{Efficiency rate} \\
E_d & \quad \text{Equipment downtime} \\
E_i & \quad \text{Equipment independent events} \\
E_u & \quad \text{Equipment uptime} \\
E_\infty & \quad \text{External losses} \\
ICT & \quad \text{Ideal cycle time} \\
L & \quad \text{Loading time} \\
L' & \quad \text{Effective time} \\
L^* & \quad \text{Available time for production} \\
M_m & \quad \text{Machine malfunctioning} \\
N_{max} & \quad \text{Maximum number of parts that can be processed in ideal operative conditions} \\
N_p & \quad \text{Number of parts processed} \\
N_{in} & \quad \text{No-input state} \\
N_o & \quad \text{Net operating time} \\
N_{op} & \quad \text{Non-operational state} \\
N_{out} & \quad \text{No-output state} \\
N_{S} & \quad \text{Non-scheduled state} \\
O & \quad \text{Operational efficiency} \\
O_i & \quad \text{Operating time} \\
OEE & \quad \text{Overall Equipment Effectiveness} \\
P & \quad \text{Performance rate} \\
P_r & \quad \text{Productive state} \\
P_{non} & \quad \text{Planned non-operating time} \\
P_t & \quad \text{Process losses} \\
Q & \quad \text{Quality rate} \\
Q_l & \quad \text{Quality losses} \\
R & \quad \text{Losses rate} \\
R_p & \quad \text{Number of parts reworks} \\
S & \quad \text{Speed losses} \\
S_p & \quad \text{Number of scraps} \\
S_d & \quad \text{Scheduled down state} \\
T & \quad \text{Total losses} \\
T_t & \quad \text{Total time} \\
U_d & \quad \text{Unscheduled down state} \\
V_o & \quad \text{Value operating time}
\end{align*} 
\]

3. Typologies of production processes

Manufacturing processes can be classified in accordance with different values: the market they satisfy (hence companies operating on demand differ from companies creating stocks that are subsequently sold to the market) and the typology of production they implement (hence companies continuously manufacturing the same item differ from companies implementing a batch production of different products).

In accordance with the technological features of the resources adopted, manufacturing systems can be classified as described in the following:

- highly automated flow lines: flow lines devoted to manufacturing or assembly processes, where capital intensive resources are inserted (e.g. robots for loading and unloading, robots for manufacturing and assembly execution, CNC machines). Usually, the possibility of operating 24/24 hours and 7/7 days is allowed
- Flexible Manufacturing Systems (FMS): similar to highly automated flow lines, capital intensive resources are inserted. Nevertheless, facilities with a high degree of flexibility are chosen, in order to allow the production of a family of similar products, rather than of a unique item
- Flexible Assembly System (FAS), where flexible capital intensive facilities are devoted to assembly operations
- cellular manufacturing, where usually highly automated cells of facilities are devoted to the manufacturing or the assembly of a family of similar products
- job shop: similar facilities are grouped into the same area. Products move from one area to the next, requiring manufacturing operations. Usually movements are manually executed, by means of trailers or forklifts.
- manual assembly lines: when assembly operations, highly differing from one product to the next, are required. Usually manual execution is implemented in workstations. Movement from one workstation to the next is executed manually or by automated systems (i.e. flow lines).

This classification does not intend to be exhaustive of all manufacturing systems typologies. Nevertheless, it aims to define some models that will be useful in the following part of the paper.

4. Overall Equipment Effectiveness evaluation methodologies

4.1 Nakajima (1988, 1989) approach

Nakajima (1988, 1989) gives the pioneer definition of OEE by defining the “six big losses”, that are the main causes of idle and/or waste time. Specifically, the author classifies them as follows:

- Downtime losses ($D_l$), due to:
  - equipment failure – breakdowns
  - set-up – adjustment
- Speed losses ($S$), due to:
  - idling - minor stops
  - reduced speed
- Quality losses ($Q_l$), due to:
  - reduced yield
  - quality defects.

The first class, downtime losses, is useful for evaluating the availability of equipment (see equation (1)); the speed losses address the computation of the performance efficiency of equipment (see equation (2)); the last class evaluates lost time spent in producing defective parts or for reworking (see equation (3)). Now the methodology
proposed for the calculation of OEE is shown and summarised in figure 1 and equations (11) and (12).

\[ A = \frac{O_t}{L_t} \]  
where \( O_t = T_t - D_t \)  
with \( O_t \) Operating time, \( L_t \) Loading time, \( T_t \) Total time, \( P_{no} \) Planned non-operating time.

\[ P = \frac{No_t}{O_t} \]  
where \( No_t = O_t - S_t \)  
with \( No_t \) Net operating time. Alternatively, \( P \) is evaluated as described in equation (6):

\[ P = \frac{N_p \times ICT}{O_t} \]  
with \( N_p \) Number of parts processed, ICT Ideal cycle time.

\[ Q = \frac{V_o}{No_t} \]  
where \( V_o = No_t - Q_o \)  
with \( V_o \) Value operating time. Alternatively, \( Q \) is evaluated as described in equation (9):

\[ Q = \frac{N_p - (S_p + R_p)}{N_p} \]  
with \( S_p \) Number of scraps, \( R_p \) Number of parts reworks.

Hence \( OEE = A \times P \times Q \)  
or alternatively \( OEE = \frac{V_o}{L_t} \)

### 4.2 Ames et al. (1995) approach

In Ames et al. (1995) guidelines, a classification of equipment losses, subsequently adopted for the calculation of OEE, is presented. As a consequence, the following machine states are defined:

- **Equipment uptime** \( (Eu_t) \), including:
  - productive state \( (Ps) \): time for regular production, production tests, engineering production, reworking, on-the-job training, loading/unloading
  - stand by state: when there is no operator and/or no product, i.e. waiting for results of production tests
  - engineering state: during which process engineering and equipment engineering occur

- **Equipment downtime** \( (Ed_t) \), including:
  - scheduled downtime, due to set-up, preventive maintenance, change of consumables

- **Operating time** \( (O_t) \)
- **Downtime losses** \( (D_l) \)
- **Availabilty** \( (A) \)
- **Performance** \( (P) \)
- **Quality** \( (Q) \)
- **Value operating time** \( (Vo_t) \)
- **Quality losses** \( (Q_L) \)
- **Ideal cycle time** \( (ICT) \)
o unscheduled downtime, due to unscheduled maintenance
- Non-Scheduled state (NSs) (i.e. for holidays, weekends, un-worked shifts).

These equipment states are the basis for calculating OEE, which includes three contributions similar to those occurring in the Nakajima (1988, 1989) approach:

\[ A = \text{Eu}_i / T_i \]  \hspace{1cm} (12)

where \( T_i = \text{Ed}_i + \text{NSs} \)  \hspace{1cm} (13)

\[ \text{Eu}_i = \text{Q} \) if \( \text{ED}_i + \text{NSs} = \text{Pno}_e + D_i \]  \hspace{1cm} (14)

\[ P = E \times O_i \]  \hspace{1cm} (15)

where \( E = \text{Efficiency rate} = \text{ICT} / \text{ACT} \)  \hspace{1cm} (16)

\[ O_i = \text{Operational efficiency} = Ps / \text{En}_i \]  \hspace{1cm} (17)

with ACT Actual cycle time.

In figure 2 the relation between total time, equipment uptime, equipment downtime and operating time is shown.

Finally, the quality rate is calculated with the same method used by the Nakajima (1988, 1989) approach, hence using equation (9). As a consequence, OEE is evaluated by equation (10).

This OEE computation procedure is particularly useful for a capital intensive manufacturing system, where the problem of not stopping manufacturing resources is particularly felt and where plants can operate, also during night or week end, with a lower minimum amount of required operators. Hence, in this formulation of OEE all stops, both planned and unplanned ones, impact negatively on the final result. Furthermore, capital intensive manufacturing systems are extremely capacity constrained, given increments of capacity following only an in-depth evaluation of further investments. Hence OEE helps managers in optimally using available resources also, eventually, in initially not scheduled time (Huang et al. 2003).

4.3 De Ron and Rooda (2005) approach

As commented in De Ron and Rooda (2005), OEE criticalities highlighted in literature are strictly related with ambiguities in definitions and measurements of its components. Hence, further specifications are presented by the authors. Furthermore, OEE is greatly impacted by factors beyond the facility itself, including operator availability and performance, equipment and material availability, along with scheduling performance, so De Ron and Rooda (2005) divide the causes of losses into equipment dependent and independent events (\( E_i \)).

A new classification of machine states is introduced, by assuming as a basis the Ames et al. (1995) approach:

- no-output state (Nout): the equipment is in the condition to perform but is unable to release items due to a lack of buffer space
- unscheduled down state (Ud): equipment is not in a condition to perform its intended functions due to equipment dependent unplanned downtime events
- scheduled down state (Sd): equipment is not available to execute its intended functions due to equipment dependent planned downtime (i.e. preventive maintenance)
- productive state (Ps): equipment is performing its intended functions.

In figure 3 main elements participating to OEE evaluation are shown and subsequently OEE components are computed.

\[ E_i = \text{Nop}_e + \text{Nin}_e + \text{Nout}_e \]  \hspace{1cm} (18)

\[ L_i = T_i - E_i \]  \hspace{1cm} (19)

\[ A = \frac{Ps}{L_i} \]  \hspace{1cm} (20)

\[ R = \frac{N_p}{N_{max}} \]  \hspace{1cm} (21)

Subsequently, \( Q \) is computed as described in equation (9) and OEE as described in equation (10), where \( P \) is substituted by \( R \), the losses rate.

Figure 3. De Ron and Rooda (2005) OEE evaluation approach

The authors exclude from the analysis all losses that are classified as equipment-independent (i.e. losses due to lack of input, lack of buffer space, non-operational activities). Rather, importance is given to time for scheduled and unscheduled downtime stops. Hence, such OEE definition is particularly useful when \( E_i \) cover an important portion of events under analysis. Their exclusion both focuses attention on equipment dependent events and isolates \( E_i \), highlighting their effect on the system.

Nevertheless, as the authors themselves note, the classification of equipment-dependent and equipment-independent losses may lead to different results. Setups
are the result of a scheduling operation, hence may be
classified as equipment independent events. Alternatively,
the way a set-up is performed depends on the ease of
execution of the setup for the analysed facility and
influences the time that the equipment is non-productive.
Hence, in order to assure repeatability of measures, a strict
classification is required for each company.

4.4 Wauters and Mathot (2007) approach
The authors define three causes of losses, so all downtime,
speed and quality losses can be subdivided by their direct
causes:
- machine malfunctioning (Mm): a machine part does
  not fulfil its expected functions and generates a loss
- process losses (Pr), due to the incorrect use of
equipment
- external losses (Ex): causes of losses that cannot be
  controlled by the production or maintenance
  function.
Nevertheless, in the classification of external losses a
degree of freedom is available. Consider reduced speed
due to lack of demand. It could be classified as an external
speed loss, if only the production and maintenance
department are responsible for OEE improvements.
Otherwise, if the commercial function is included too, a
commercial campaign for incrementing demand could be
promoted as a corrective action and as a consequence
reduced speed due to lack of demand could be classified
as an internal cause due to process.
The diagram in figure 4 shows the relationship between
analysed losses.

![Figure 4. Wauters and Mathot (2007) approach for OEE computation](image)

Hence, the authors evaluate OEE as described in equation
\( \text{OEE} = \frac{V_o}{L_o} \)

\[ (22) \]

where \( L_o = T_t - Ex \)

\[ (23) \]

\( V_o = L_o - T_t \)

\[ (24) \]

\( T_t = Mm + Pr \)

\[ (25) \]

with \( T_t \) Total losses.

5. Discussion
Main differences among methodologies presented lay in
availability factor computation and in particular in key-
losses for each manufacturing system.

Specifically, in capital intensive manufacturing/assembly
systems (i.e. highly automated flow lines, FMS, FAS,
cellular systems) the implementation of a flow as
continuous as possible is a primary objective. All stops,
both planned and unplanned, are key stops. Hence, for
capital intensive manufacturing systems Ames et al. (1995)
OEE computation approach is addressed (see table 1),
since the time base for the analysis is the total time. Also
Wauters and Mathot (2007) will allow interesting results if
the majority of the stops will be classified as internal
losses and the responsible for the execution of corrective
actions will be identified. Otherwise, in job shop and
manual assembly lines, along with in manual workstations
included in FMS, FAS or cellular layout configurations,
some planned stops are unmodifiable (i.e. because
contractual constraints exist). Hence, the focus is on the
optimisation of internal causes of losses and on the
identification of factors and events influencing their
occurrence. As a reference basis time is assumed a portion
of the total time, that portion on which improvements
could be implemented. Hence, OEE approaches
proposed by Nakajima (1988, 1989) and De Ron and
Rooda (2005) are addressed. Also Wauters and Mathot
(2007) will allow to obtain good results in job shop and
manual assembly lines (along with with in flexible automated
manufacturing systems including manual workstations) if,
on the contrary as previously stated for the case of capital
intensive manufacturing/assembly systems, a strict
distinction is executed between losses whose reduction
and/or elimination is expected by the company itself and
those named as external. Obviously, as underlined by
the authors, responsibilities crucial for the implementation of
corrective actions should be identified.

Finally, analysed OEE evaluation methodologies are
studied in terms of their degree of repeatability of losses
classification and final OEE results. Whilst Ames et al
(1995) is characterised by a high degree of repeatability,
given the use of \( T_t \) as reference time and the crucial, but
simple, distinction between scheduled and unscheduled
and Wauters and Mathot (2007) are characterised by a low
degree of repetitiveness of results, since used losses classifications are highly operators dependent and an accepted and shared standard is required to fit each company for assessing OEE comparisons year by year. Otherwise errors can be induced and a distortion of results could emerge.

<table>
<thead>
<tr>
<th>Highly automated flow lines</th>
<th>FMS</th>
<th>Job shop</th>
<th>Manual assembly lines</th>
<th>Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular manufacturing</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>1.</td>
</tr>
<tr>
<td>Ames et al. (1995)</td>
<td>X</td>
<td></td>
<td></td>
<td>H</td>
</tr>
</tbody>
</table>

Legend: H = high  L = low

Table 1. Relation between production process typology and OEE formulations

6. Conclusions

In this paper four methods for OEE calculation are presented and compared in order to address practitioners in the selection process, that usually emerges both when a new product is inserted into the market and when a continuous improvement of existing production/assembly processes is implemented. Specifically, guidelines addressing their application both in capital intensive systems and in companies with manual assembly/production processes are traced.

Future researches will be addressed to the analysis of alternative OEE indexes defined for the whole of the factory rather than to single machines included.

References


