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On the Analysis of Effectiveness in a Manufacturing Cell: A Critical Implementation of Existing Approaches

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Abstract

OEE (Overall Equipment Effectiveness) is a widely used indicator in the evaluation of effectiveness of manufacturing systems. However, several authors published alternative approaches for its computation, complicating the implementation step for practitioners. This study analyses the literature regarding OEE, selects four main methodologies for its evaluation and examines the underlying differences between them. A real life case study is analysed to illustrate problems arising during data collection and the differences in results obtained, together with traceable conclusions for improving the performance of production systems, both in traditional and in innovative industrial plants, following Industry 4.0 principles.

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Keywords: OEE - Overall Equipment Effectiveness, manual and automated manufacturing systems, Industry 4.0

1. Introduction

The development in recent decades towards a global economy and the last global economic recession has intensified the need for manufacturing companies to improve their competitiveness. In order to retain and improve the ability to compete in the market, productivity optimisation has become a central issue, which can be achieved by

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detection and elimination of production losses. In such a context, process measurement and evaluation plays an important role in understanding the current operational performance and in recognising possibilities for improvement (Or 2010).

Overall Equipment Effectiveness (OEE) is a tool for monitoring how manufacturing resources' time is allocated and identifying those margins available for improvement. Specifically, OEE is computed from an initial operational environment and subsequently monitored at regular time intervals, in order to evaluate the existence and effectiveness of upgrades, implemented and consolidated year by year, as suggested by the Total Quality Management (TQM) approach (Kumar et al., 2009). Furthermore, OEE is particularly useful when the production of new items is carried out using existing resources and whose operating conditions are preferably modified as little as possible. As described in Gamberini et al. (2006, 2009a, 2009b), changing the operating conditions of manufacturing resources incurs costs, related to: acquisition of deficient knowledge, execution of new working procedures, execution of new maintenance operations and setting of new workstations. Hence, OEE is a tool for evaluating the future performance of manufacturing resources and comparing them with the initial situation by considering alternative operational scenarios. Specifically, those processes with high standards of quality and throughput are addressed (De Groote 1995). This context is of particular interest for the development of Industry 4.0 principles and for supporting their implementation in real life production environment.

Published contributions on OEE mainly focus on three different research fields. The first describes OEE using different definitions proposed by the various authors. The second addresses using and computing OEE. The third considers the extension of the OEE index, such as by: Sherwin (2000) who proposed Overall Process Effectiveness to measure the performance of entire processes; Oechsner et al. (2003) who proposed a metric for the evaluation of effectiveness of an entire factory; Garza-Reyes et al. (2008) who developed Overall Resource Effectiveness, which considers material efficiency; Braglia et al. (2008) who presented Overall Equipment Effectiveness of a manufacturing line; Ahire and Relkar (2012), who correlated OEE and FMEA approaches, Andersson and Belgran (2015) who combined OEE and productivity analysis as a driver for improvement;

This paper focuses on OEE formulations for singular equipment and particularly on four alternative approaches proposed by Nakajima (1988, 1989), Ames et al. (1995), De Ron and Rooda (2005) and Wauters and Mathot (2007). Their application to the study of effectiveness of an automated productive cell is presented. Specifically, differences emerging during data collection, OEE computation (and particularly during the computation of the component named availability), results analysis and the definition of future actions for improvement are underlined. The topic of problems emerging in OEE data collection and computation is a recent and consistent problem, recently presented also in Hedman et al. (2016), where the aspect of automated collection of data is studied.

The paper is organised as follows. Section 2 presents the alternative aforementioned formulations. In section 3, a real life case study is proposed; specifically, the computation of effectiveness of a manufacturing cell is faced. Section 4 presents a discussion of results and finally, section 5 offers conclusions.

2. Alternative formulations for OEE

In the following, alternative formulations of OEE are presented, by considering those most used in practice (i.e. in automated computation and in multi-criteria approaches, as reported respectively in Singh et al. 2013 and in da Silva et al. 2017) and cited in literature.

2.1. Nakajima (1988, 1989) approach

Nakajima (1988, 1989) gave the pioneer definition of OEE by describing the "six big losses" that are the main causes of idle and/or wasted time. Specifically, the author classifies them as follows: Downtime losses (D_l), due to equipment failure, breakdown, set-up, adjustment; Speed losses (S_l), due to idling, minor stops, reduced speed; Quality losses (Q_l), due to reduced yield, quality defects.

As a consequence, the OEE is computed as described in equations (1)-(8):

$$OEE = A * P * Q \quad (1)$$

where:

$$A = Availability = O_t / L_t \quad (2)$$

$O_t = Operating\ time = L_t - D_l$ (3)
$L_t = Loading\ time = T_t - Pno_t$ (4)
$P = Performance\ rate = No_t / O_t$ (5)
$No_t = Net\ operating\ time = O_t - S_l$ (6)
$Q = Quality\ rate = Vo_t / No_t$ (7)
$Vo_t = Value\ operating\ time = No_t - Q_l$ (8)
with T_t Total time and Pno_t Planned non-operating time.

2.2. Ames et al. (1995) approach

Ames et al. (1995) presented an alternative classification of equipment losses, subsequently adopted for the calculation of OEE. Specifically, the following machine states are defined:

- Equipment uptime (Eu_t), including the productive state (Ps), that is the time for regular production, production tests, engineering production, reworking, on-the-job training, loading/unloading, the standby state, when there is no operator and/or no product, i.e., waiting for results of production tests and the engineering state, during which process engineering and equipment engineering occur
- Equipment downtime (Ed_t), including the scheduled downtime, due to set-up, preventive maintenance, change of consumables and the unscheduled downtime, due to unscheduled maintenance
- Non-Scheduled state (Ns_s), i.e. for holidays, weekends and un-worked shifts.

OEE is subsequently calculated as described in equation (1), nevertheless A and P are computed as described in equations (9)-(13).

$A = Eu_t / T_t$ (9)
where:
$T_t = Eu_t + Ed_t + Ns_s$ (10)
$P = E * O_e$ (11)
$E = Efficiency\ rate = ICT / ACT$ (12)
$O_e = Operational\ efficiency = Ps / Eu_t$ (13)
ICT is the Ideal Cycle Time and ACT is the Actual Cycle Time.

2.3. De Ron and Rooda (2005) approach

The De Ron and Rooda (2005) classification of losses is strictly connected to the definition of equipment dependent and independent events (Ei_e). Hence, a new classification of machine states is introduced, assuming the approach of Ames et al. (1995) as a basis:

- non-operational state (Nop_s): equipment is not scheduled to perform its intended functions (i.e., due to holidays, weekends, engineering activities)
- no-input state (Nin_s): equipment is in the condition to perform but is unable to operate due to a lack of input items
- no-output state ($Nout_s$): equipment is in the condition to perform but is unable to release items due to a lack of buffer space
- unscheduled down state (Ud_s): equipment is not in a condition to perform its intended functions due to equipment dependent unplanned downtime events
- scheduled down state (Sd_s): equipment is not available to execute its intended functions due to equipment dependent planned downtime (i.e., preventive maintenance)
- productive state (P_s): equipment is performing its intended functions.

Again, differences with aforementioned approaches are focused on the computation of A (see equation 14) and P, here substituted by the losses rate R, which compares parts processed and their maximum reachable value during P_s.

$A = P_s / L'_t$ (14)
where:
$L'_t = Effective\ time = T_t - Ei_e$ (15)

$$Ei_e = Nop_s + Nin_s + Nout_s \quad (16)$$

2.4. Wauters and Mathot (2007) approach

The authors defined three causes of losses, such that all downtime, speed and quality losses can be subdivided by their direct causes:

- machine malfunctioning (Mm_l): a machine part does not fulfil its expected functions and generates a loss
- process losses (Pr_l), due to the incorrect use of equipment
- external losses (Ex_l): causes of losses that cannot be controlled by the production or maintenance function.

Hence, the authors evaluated OEE as described in equation (17), where L_t'' indicates the available production time, computed as described in equation (18):

$$OEE = Vo_t/L_t'' \quad (17)$$

where:

$$L_t'' = T_t - Ex_l \quad (18)$$

$$Vo_t = L_t'' - Mm_l - Pr_l \quad (19)$$

3. Case study

The aforementioned OEE formulations are now applied in a real-life case study in order to highlight their differences. Specifically, the manufacturing system under analysis is a cell, depicted in Figure 1, with the possibility of operating without the assistance of operators in a night-time shift.

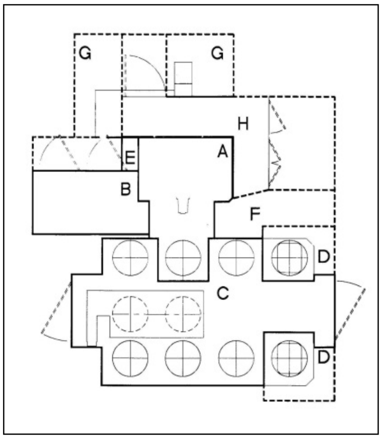

Figure 1. Scheme of the cell under analysis

Equipment belonging to the cell are as follows:

A. Working centre
B. Tools storage
C. Pallet storage
D. Load/unload pallet
E. Load/unload tools
F. Control centre
G. Scraps and water deposit.

The planned production is for five days per week; two working shifts per day with the presence of an operator and one shift per day without the presence of an operator (during the night). The length of each daytime working shift with the presence of the operator is seven and a half hours. The length of the night-time shift without the presence of the operator is nine hours. Such a shift is not always inserted in the planning but only when extra production is required in order to meet deadlines.

The system has been observed for 4 months. Data are collected by means of a specific sheet, whose relevant information is reported as follows:

- general information: operator code, date
- daytime shift (section repeated per each available shift): type and quantity of items produced, time required by setup, failure type and time required for repairing activities, time spent for washing and workstation restoration at the end of shift, other types of non-productive time interval (description and amount)
- night-time shift: type and quantity of items produced, time spent for washing and workstation restoration at the end of shift, other types of non-productive time interval (description and amount).

Collected data are summarised in Table 1 and described in the following:

- T_t, the calendar time, obtained by considering 24 available hours per each day
- unscheduled production time due to weekends and holidays
- unscheduled portion of the night-time shifts
- time dedicated to preventive maintenance
- time required for change of consumables
- intervals devoted to process and equipment engineering
- cell standby induced by lack of input
- cell standby induced by lack of space in buffers
- time required for setup
- stops due to unscheduled downtime.

Such data are used in the following for evaluating OEE in accordance with the aforementioned formulations. Specifically, criticalities in computing P have been analysed in the past by Gouvêa Da Costa and Pinheiro De Lima (2002). Q is similarly evaluated by each studied methodology and set to a value of 0.98. Rather, efforts are focused on the alternative A computation equations and their effects on OEE and the final results.

Table 1: Collected data

Month	T_t	Weekends and holidays	Unscheduled shift	Preventive maintenance	Change of consumables	Process and equipment engineering	Standby due to input waiting	Standby due to buffer space waiting	Setup	Unscheduled downtime
1	696	192	92,37	8	40	7,5	5	1	45	24,88
2	744	216	102,25	8	40	0	4,75	0	37,80	22,19
3	720	264	30,26	10	50	7,5	4,80	0	64	31,62
4	744	216	136,12	8	40	0	3	0,45	25	11,25

3.1. Nakajima (1988, 1989) approach implementation in the case study

Table 2 shows the values of $\boldsymbol{A}$ and OEE computed by following guidelines reported in Nakajima (1988, 1989). $\boldsymbol{L_t}$, the loading time planned for production, is obtained by considering the duration of daytime shifts with the required portion of night-time shift necessary to satisfy due dates.

Table 2: Nakajima (1988, 1989) A and OEE

Month	T_t	L_t	D_l	O_t	A	OEE
1	696	363,63	69,88	293,75	0,81	0,76
2	744	377,75	59,99	317,76	0,84	0,79
3	720	365,74	95,92	270,12	0,74	0,70
4	744	343,88	36,25	307,63	0,90	0,84

3.2. Ames et al. (1995) approach implementation in the case study

Table 3 shows the values of A and OEE computed by following guidelines reported in Ames et al. (1995). Ns_s considers only the unscheduled time during weekends, holidays and unnecessary night-time shifts, given the production planning hypothesised. Eu_t is computed by subtracting from T_t both Ns_s and the unscheduled and scheduled downtime (due to preventive maintenance, change of consumables and setup). Ps is evaluated by considering the effect of engineering activities and the presence of standby intervals.

Table 3: Ames et al. (1995) A and OEE

Month	T_t	NSs	Eu_t	A	Ps	OEE
1	696	284,37	293,75	0,42	280,25	0,38
2	744	318,25	317,76	0,43	313,01	0,40
3	720	294,26	270,12	0,38	257,82	0,34
4	744	352,12	307,63	0,41	304,18	0,38

3.3. De Ron and Rooda (2005) approach implementation in the case study

The values of A and OEE computed by following guidelines traced in the approach of De Ron and Rooda (2005) are shown in Table 4. Nop_s includes both unscheduled time during weekends, holidays and unnecessary night-time shifts, given the production planning hypothesised, together with time dedicated to engineering activities. Subsequently, L'_t is evaluated by also considering standby intervals and Ps by subtracting unscheduled and scheduled down states.

Table 4: De Ron and Rooda (2005) A and OEE

Month	T_t	Nop_s	L'_t	Ps	A	OEE
1	696	291,87	398,13	280,25	0,70	0,68
2	744	318,25	421,00	313,01	0,74	0,71
3	720	301,76	413,44	257,82	0,62	0,60
4	744	352,12	388,43	304,18	0,78	0,75

3.4. Wauters and Mathot (2007) approach implementation in the case study

Table 5 shows the OEE results for the case where the approach of Wauters and Mathot (2007) is implemented. Specifically, as aforementioned, the distinction between external and technical losses should be executed per each loss type (downtime, speed and quality related). However, only the elaboration of the input data focused on in the paper is reported in the following.

Table 5: Wauters and Mathot (2007) A and OEE

Month	T_t	L''_t	OEE
1	696	363,63	0,75
2	744	377,75	0,80
3	720	365,74	0,68
4	744	343,88	0,86

4. Discussion

In the aforementioned approaches for the computation of OEE, the main differences are related to the reference time and the classification of losses.

Specifically, whilst Ames et al. (1995) refer to T_t, Nakjima (1988, 1989), De Ron and Rhooda (2005) and Wauters and Mathot (2007) refer only to a portion of it. Thus, variations in the time dedicated to weekend stopping or holidays consistently influence the OEE values obtained by Ames et al. (1995). Tables 6 and 7 report the variations obtained in A and OEE, when computed by the Nakajima (1988, 1989) approach and when a 10% and 50% reduction of unscheduled time during weekends or holidays occurs, respectively. No further modifications are considered in order to underline the relations among the data.

Table 6: A and OEE obtained by the Nakajima (1988, 1989) approach with a 10% reduction in stopping during weekends and holidays

Month	T_t	L_t	D_l	O_t	A	ΔA	OEE	ΔOEE
1	696	382,83	69,88	312,95	0,82	1,19%	0,77	1,19%
2	744	399,35	59,99	339,36	0,85	1,02%	0,80	1,02%
3	720	392,14	95,92	296,52	0,76	2,38%	0,71	2,38%
4	744	365,48	36,25	329,23	0,90	0,70%	0,85	0,70%

Table 7: A and OEE obtained by the Nakajima (1988, 1989) approach with a 50% reduction in stopping during weekends and holidays

Month	T_t	L_t	D_l	O_t	A	ΔA	OEE	ΔOEE
1	696	459,63	69,88	389,75	0,85	4,97%	0,80	4,97%
2	744	485,75	59,99	425,76	0,88	4,20%	0,82	4,20%
3	720	497,74	95,92	402,12	0,81	9,39%	0,76	9,39%
4	744	451,88	36,25	415,63	0,92	2,82%	0,87	2,82%

Even if a reduction in stopping time during weekends or holidays is registered in the consistent range [10%, 50%], improvements in A and OEE are limited in the range [0.70%, 9.39%]. Therefore, such a corrective action is discouraged when alternatives are available, even if recent developments in Industry 4.0 could support it.

A different effect occurs with the implementation of the Ames et al. (1995) approach, whose results are reported in Tables 8 and 9. Specifically, variations of A and OEE proportional to the amount of stopping time reductions imposed are registered in the range [6.54%, 48.87%] and [6.85%, 51.20%], respectively, addressing the desirability of the related corrective action. The approaches of De Ron and Rooda (2005) and Wauters and Mathot (2007) have a behaviour similar to the Nakajima (1988, 1989) formulation.

Table 8: A and OEE obtained by the Ames et al. (1995) approach with a 10% reduction in stopping during weekends and holidays

Month	T_t	NSs	Eu_t	A	ΔA	Ps	OEE	ΔOEE
1	696	265,17	312,95	0,45	6,54%	299,45	0,40	6,85%
2	744	296,65	339,36	0,46	6,80%	334,61	0,42	6,90%
3	720	267,86	296,52	0,41	9,77%	284,22	0,37	10,24%
4	744	330,52	329,23	0,44	7,02%	325,78	0,41	7,10%

Table 9: A and OEE obtained by the Ames et al. (1995) approach with a 50% reduction in stopping during weekends and holidays

Month	T_t	NSs	Eu_t	A	ΔA	Ps	OEE	ΔOEE
1	696	188,37	389,75	0,56	32,68%	376,25	0,51	34,26%
2	744	210,25	425,76	0,57	33,99%	421,01	0,53	34,50%
3	720	162,26	402,12	0,56	48,87%	389,82	0,51	51,20%
4	744	244,12	415,63	0,56	35,11%	412,18	0,52	35,51%

Therefore, the adoption of the Ames et al. (1995) approach is addressed in capital intensive manufacturing/assembly systems (i.e., highly automated flow lines, FMS, FAS, cellular systems, automated processes following Industry 4.0 principles) where the reduction of each type of loss is a primary objective and lower constraints exist in using equipment 24 hours per day, 7 days a week.

Otherwise, when operators are the main resources (i.e., in job shop, in manual assembly lines or in FAS with a consistent integration between manual and automated workstations) constraints exist in frequently modifying the work timetable. Preferably, attention is paid to losses related strictly to the analysed manufacturing system and its behaviour during its planned work. Hence, the approaches of Nakajima (1988, 1989) or De Ron and Rooda (2005) or Wauters and Mathot (2007) are addressed. Nevertheless, in contrast to Ames et al. (1995), as these formulations exclude a portion of losses from the OEE computation (i.e., Pno_t in Nakajima (1988, 1989), Nop_s, Nin_s, $Nout_s$ in De Ron and Rooda (2005) and Ex_l in Wauters and Mathot (2007)), a standard for the classification of losses should be introduced into each company in order to ensure repeatability of results both year by year and when OEE is computed by different operators.

An example of diverse values of OEE obtained by different classifications of losses is reported in the following. In Tables 2 and 5, engineering activities have been classified as strictly connected with production, even if they introduce losses. Specifically, if the Nakajima (1988, 1989) approach is implemented, engineering activities affect the computation of P by introducing speed losses in the process. Alternatively, if the Wauters and Mathot (2007) approach is implemented, engineering activities introduce a technical process loss. If time spent for engineering activities is classified as a planned interval, the OEE values obtained are as reported in Tables 10 and 11 for the Nakajima (1988, 1989) and Wauters and Mathot (2007) approaches, respectively.

Table 10. A and OEE obtained by the Nakajima (1988, 1989) approach when engineering activities are classified as planned operations

Month	T_t	L_t	D_l	O_t	A	ΔA	OEE	ΔOEE
1	696	356,13	69,88	286,25	0,80	-0,50%	0,756	-0,50%
2	744	377,75	59,99	317,76	0,84	0,00%	0,791	0,00%
3	720	358,24	95,92	262,62	0,73	-0,74%	0,690	-0,74%
4	744	343,88	36,25	307,63	0,90	0,00%	0,842	0,00%

Table 11. A and OEE obtained by the Wauters and Mathot (2007) approach when engineering activities are classified as planned operations

Month	T_t	L''_t	OEE	ΔOEE
1	696	356,13	0,763	2,11%
2	744	377,75	0,804	0,00%
3	720	358,24	0,698	2,09%
4	744	343,88	0,858	0,00%

Specifically, if the Nakajima (1988, 1989) approach is implemented, such a new classification means that engineering activities fall in Pno_t, while if the Wauters and Mathot (2007) formulation is adopted, engineering activities are classified as Ex_l. Differences in the computation of OEE reach up to -0,74% in the former case and up to 2,11% in the latter.

No modifications in the OEE computed in Tables 3 and 4 by the Ames et al. (1995) and De Ron and Rooda (2005) approaches, respectively, are registered. However, modifications in OEE computed by the De Ron and Rooda (2005) formulation could emerge in accordance with the adopted setup losses classification; this is something that can be debated. Setups result from scheduling, which is an equipment-independent activity. Alternatively, it could be argued that the way in which setups are carried out and the time equipment is non-productive, depends on how easily setups for the particular equipment can be carried out. Hence, setup could be classified as an equipment-dependent operation. Obviously, different OEE values are obtained in accordance with the hypothesis set.

Conclusions

This paper has investigated main literature regarding the OEE index and particularly, the focus is on four different approaches for the computation of effectiveness. Whilst the approach of Ames et al. (1995) is addressed when capital intensive manufacturing/assembly systems are studied (i.e., highly automated flow lines, FMS, FAS, cellular systems, automated processes following Industry 4.0 principles), the Nakajima (1988, 1989), De Ron and Rooda (2005) or Wauters and Mathot (2007) approaches are suggested when job shop, manual assembly lines, or FAS with a consistent integration between manual and automated workstations are analysed. However, the Nakajima (1988, 1989), De Ron and Rooda (2005) or Wauters and Mathot (2007) approaches are characterised by results repeatability only if a standard for losses classification is introduced into each company, as a portion of losses is excluded from the analysis, in accordance with authors' formulation.

A real-life case study is finally proposed and the four aforementioned approaches are compared in order to underline the different results obtained, the addressed fields of application and the characteristics and expected corrective actions.

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