A REVIEW OF LITERATURE ON OVERALL EQUIPMENT EFFECTIVENESS (OEE)

Neelakandan B.[1] and Dr. C. Muralidharan[2]

[1]*Assistant professor, Manufacturing Engineering and* [2]*Professor, Manufacturing Engineering,*
Annamalai University, Annamalinagar 608002, Tamil Nadu, India. neelakandan78@rediffmail.com / bnkapmfgewddeau04@gmail.com and Annamalai University, muralre@yahoo.co.in

Abstract **-** To compete in the challenging global business scenario manufacturing industries are constantly strive to improve manufacturing productivity and equipment utilization. The concept of overall equipment effectiveness (OEE), is becoming increasingly popular, is being widely used as a quantitative tool for performance measurement at equipment level and is accepted as the primary performance metric beyond equipment to performance of whole factory. The review indicates that OEE and its extension are used as an index to evaluate the performance of particular equipment or a subsystem, and that there is a lack of standard method to evaluate the effectiveness of the entire system irrespective of configuration. The review also broadcasts, that the time taken for inspection and resources involved for inspection are not accounted so far.

I. INTRODUCTION

A well-known and widely spread concept of improving the production performance is total productive maintenance (TPM) founded by Nakajima (1988). Nakajima**,** developed TPM by combining the key features of preventive, productive and predictive maintenance with TQM, QCs and employee involvement. As Ahuja and Khamba (2008) say, "TPM is a production-driven improvement methodology that is designed to optimize equipment reliability and ensure efficient management of plant assets through the use of employee involvement, linking manufacturing, maintenance and engineering.

II. REVIEW OF LITERATURE (FRAME OF REFERENCE)

Seiichi Nakajima proposed the back bone of TPM metric OEE. A number of literatures are available dealing with OEE e.g. Leachman (1997), Ljungberg (1998), Jonsson and Lesshammar (1999), Dal et al. (2000), Jeong and Phillips (2001), DaCosta and Da Lima (2002), Huang et al., (2002), Huang et al.,(2003) Bamber et al. (2003), De Ron and Rooda (2005, 2006), Nachiappan and Anantharaman (2006), Muthiah and Huang (2007), Muthiah et al. (2008), Muchiri and Pintelon (2008), and Braglia et al. (2009).Most of researchers deal directly with the technical aspects of OEE while some with alternative measures.

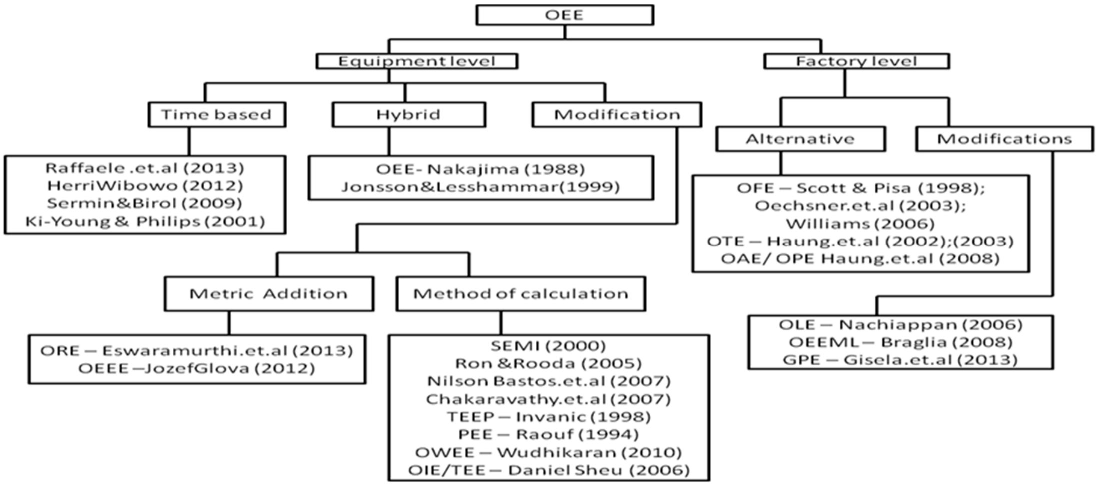

Figure 1 Classification of OEE literature

The literature on OEE can be broadly classified into two major categories, namely(i) equipment and (ii) factory level. Further, equipment can be branched into time based, hybrid and modification.(Figure 1) The researchers widely accepted, that the performance of an equipment can be measured using the three dimensions, Availability (A), Performance (P), Quality (Q) and their product as OEE. In time based all the three dimensions are evaluated purely with respect to time only. In hybrid the performance and quality are evaluated either with time, output, parts produced, or with volume whereas availability is still measured only with time. If any, additional metrics added along with traditional OEE then it is classified under modification. OEE in factory level is sub divided into two: as alternative and modifications. Most of the researchers derived their own metric as an alternative to traditional OEE to explore it at the level of entire manufacturing unit, marking under alternative. Some researchers added dimensions or clubbed dimensions and referred here as modification.OEE metrics coined by the researchers focused at equipment level-. modification models- metric.

I. Equipment level - time based models

Here all the three dimensions availability, performance, and quality were evaluated in terms of time only
The formulae suggested by various authors for calculating OEE are given below.

(i.) According to Raffaele and Maria (2013), HerriWibowo (2012)

Availability (A) = $\frac{operatingtime}{loadingtime}$

Performance(P) =$\frac{netoperatingtime}{operatingtime}$

Quality(Q) =$\frac{valuableoperatingtime}{netoperatingtime}$

OEE =Availability(A) × Performance(P) × Quality(Q)

$=\frac{operatingtime}{loadingtime} \times \frac{netoperatingtime}{operatingtime} \times \frac{valuableoperatingtime}{netoperatingtime}$

i.e. OEE =$\frac{valuableoperatingtime}{loadingtime}$ ………………… (1)

(ii) Similarly Sermin and Birol (2010) calculated the same with varying nomenclature

Availability (A) =$\frac{operating\ time}{Net\ available\ time}$

Performance (P) =$\frac{net\ operating\ time}{operating\ time}$

Quality (Q) =$\frac{Fullyproductivetime}{netoperatingtime}$

i.e. $OEE = \frac{\text{fully productive time}}{\text{Net available time}}$..................... (2)

(iii) Ki-Young and Philips (2001) compared OEE by two computational methods based on theoretical calendar time as OEE1 (figure 2) and Nakajima six loss category as OEE2(figure 3) and represented as OEE $= \frac{valuable\ production\ time}{total\ time}$................ (3)

OEE 1

Time efficiency= $\frac{Actualproductiontime}{totaltime}$

Speed efficiency = $\frac{netproductiontime}{Actualavailabletime}$

Quality efficiency= $\frac{valuableproductiontime}{netproductiontime}$

OEE 2

Availability (A) = $\frac{Actualavailabletime}{totaltime}$

Performance (P) = $\frac{netproductiontime}{Actualavailabletime}$

Quality (Q) = $\frac{valuableproductiontime}{netproductiontime}$

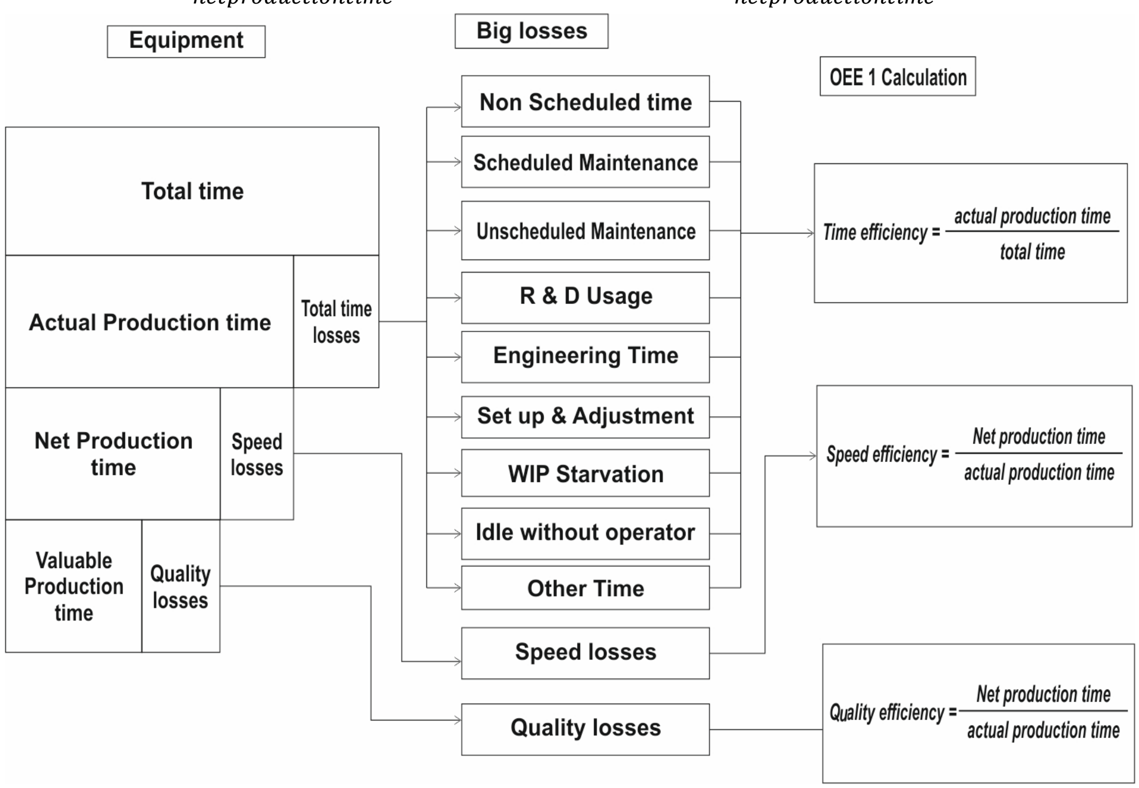

Figure 2 . Theoretical time based OEE (1)

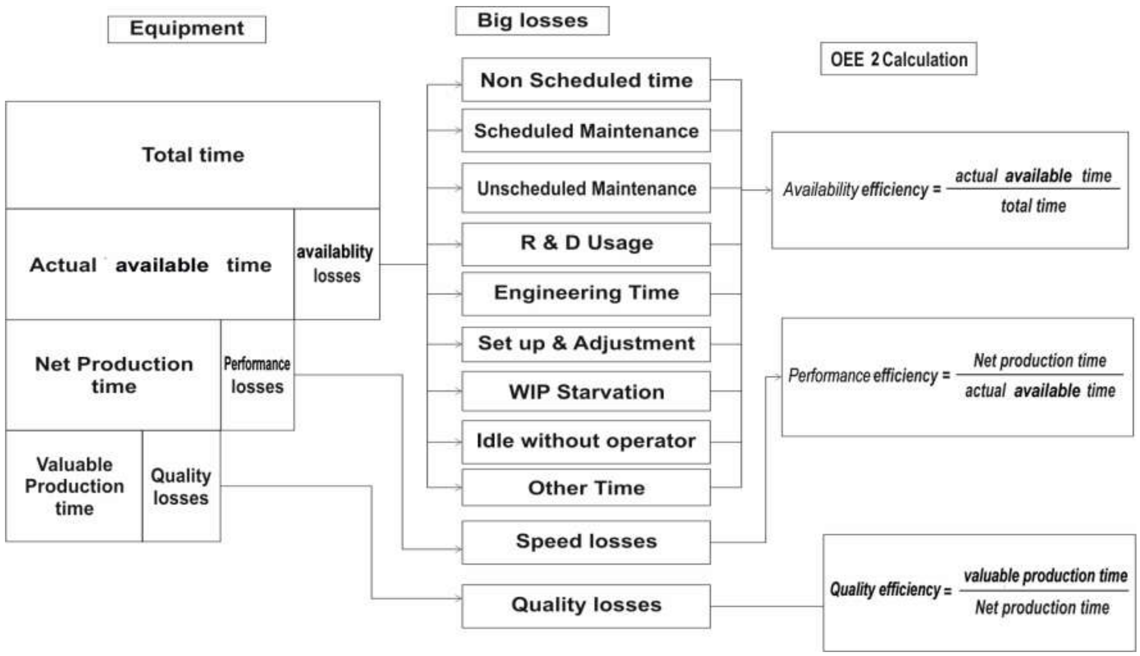

Figure 3. Nakajima six loss category based OEE(2)

Unlike above researchers most of the researchers hinged with hybrid model and they were the followers of Nakajima(1988) and De Groote(1995)

II. Equipment level –hybrid models

(i) Jonsson and Lesshammer (1999 derived OEE from the three dimensions as follows and shown in (figure 4)

Availability (A) $=\frac{loadingtime - down\ time}{loading\ time}$

Performance(P) $=\frac{idealcycletime \times output}{operatingtime}$

Quality(Q) $=\frac{Input - volumeofqualitydefects}{Input}$

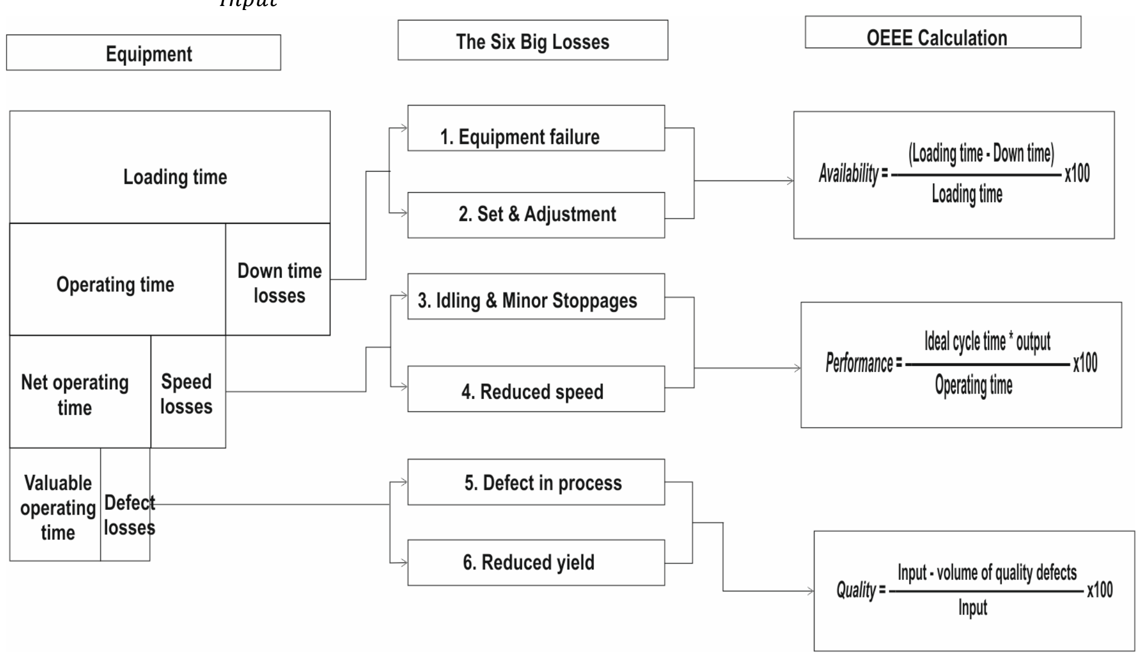

Figure 4 Jonsson and Lesshammar arrived OEE(based on Nakajima)

De Groote(1995)defined OEE as

Availability (A) $= \frac{Plannedproductiontime - Unplanneddowntime}{Plannedproductiontime}$

Performance(P) $= \frac{Actualamountofproduction}{plannedamountofproduction}$

Quality(Q) $= \frac{Actualamountofproduction - nonacceptedamount}{Actualamountofproduction}$

III.(a)Equipment level –modification models (method of calculation)

In general, in three dimensions of OEE: Availability, Performance, Quality modifications are made in any one of these dimensions.

(i) ***SEMI****(2000)*

In this approach the availability and quality remain unchanged and performance is classified into operational efficiency (OE) and rate efficiency(RE)-

OEE = AE × (OE × RE) × QE ……………………….(4)

AE $= \frac{\text{equipment uptime}}{\text{total time}}$ OE $= \frac{\text{production time}}{\text{equipment uptime}}$ RE $= \frac{\text{theoretical production time for actual units}}{\text{production time}}$

QE $= \frac{\text{theoretical production time for effective units}}{\text{theoretical production time for actual units}}$

This approach even though purely based on time models due to its expansion in the performance metric, is placed under modification category. NilsonBastosetal.(2007) and Chakravathy etal. (2007) referred to the same. Ron and Rooda (2005) also referred along with modified six big losses with respect to time.

(ii) ***T****otal* ***E****quipment* ***E****ffectiveness* ***P****erformance (TEEP)*

Invancic (1998), formulated this method on the basis of OEE.TEEP is a performance metric for the total performance of equipment based on the calendar time. Inclusion of planned down time in total planned time horizon is the major difference. This inclusion is widely accepted and practiced globally by researchers now a days. The author provided a clear vision regarding planned and unplanned down time(in availability).In the total time horizon previously planned(stated) stoppages and unplanned(minor) stoppages are accounted in evaluating the availability of the equipment. Performance and quality metrics evaluation were as on traditional OEE. Simply TEEP measures OEE against calendar time Figure 5.(ie: 24 hours/day, 365 days/year) as shown below:

TEEP$= \frac{valuableoperatingtime}{calendertime}$ = OEE$\times \frac{loadingtime}{calendertime}$

Thus OEE and TEEP are closely related measurements focusing only on equipment. The major advantage is TEEP shows how well equipment is used and this metric has to be maximized before investing more on capacity.

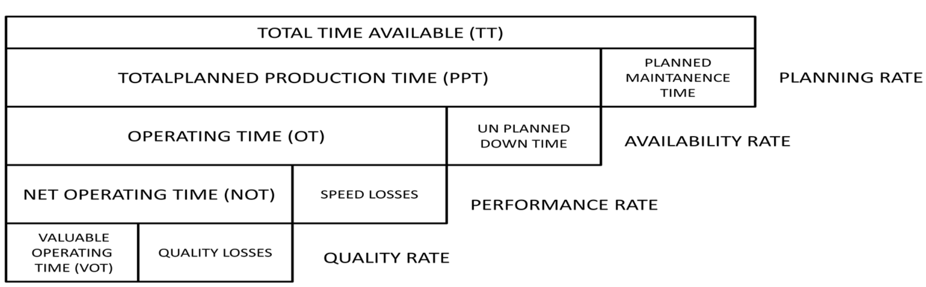

Figure 5. TEEP measures OEE against calendar time.

(iii) ***P****roduction* ***E****quipment* ***E****fficiency (PEE)*

In traditional OEE calculation all three dimensions availability, performance and quality have equal importance and weights. In contrast with traditional OEE Raouf(1994) proposed a new approach PEE as shown in (figure 6) using analytical hierarchy process where the weight of each dimensions differs from that of the other. More over Raouf's weight of discrete-type production operation differs from that for continuous process operation. Regarding discrete-type production operation he assigned weights directly to the three dimensions and PEE is calculated as

$PEE = (A^{k1})\times(P^{k2})\times(Q^{k3})$

where k_i is the weight of PEE elements (for i = 1 to 3),$0< k_i \leq 1$ and $\Sigma k_i =1$. Whereas in continuous process operation he modified the dimensions as availability (A_1), attainment (A_2), performance efficiency(E), quality rate(QR), product support efficiency (PSE) and operating utility(OU). PEE is then calculated

$PEE = (A_1)^{k1}(A_2)^{k2}(E)^{k3}\ (QR)^{k4}\ (PSE)^{k5}\ (OU)^{k6}$

where k_i is the weight of PEE elements (for i = 1 to 6),$0< k_i \leq 1$ and $\Sigma k_i =1$

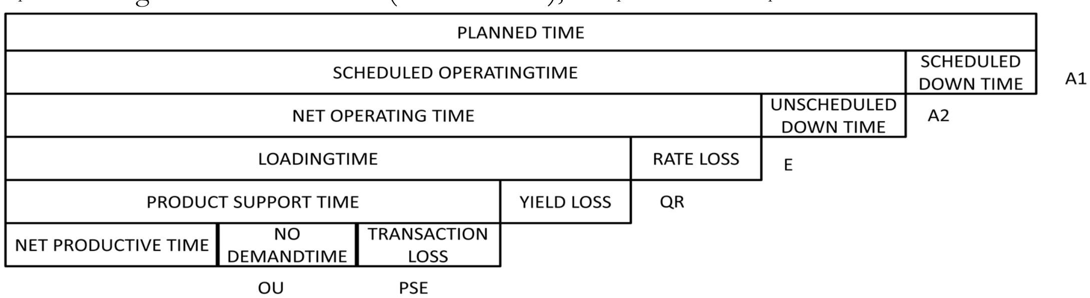

Figure 6. Raouf approach to PEE

(iv) ***O****verall* ***W****eighting* ***E****quipment* ***E****fficiency (OWEE)*

Even though Raouf's (1994)PEE is reasonable than original OEE Wudhikarn (2010) not satisfied with the weight setting method by applying analytical hierarchy process and aimed to rectify the weight setting of OEE element by OWEE. In his approach he had chosen Rank Order Centroid (ROC) proposed by Edwards and Barron(1996) and stated this approach is simpler than former. The basic elements of traditional OEE is calculated, and then ROC is utilized to specify the weight to each element. The combination of OEE value along with weights specified by ROC method gives OWEE. For specifying weight based on ROC he specified

$W_i = (\frac{1}{k})\ \Sigma^k{}_{j=1} \frac{1}{rk}$and combined with OEE metrics, OWEE is calculated by the formula, where i varies from1 to 3

$OWEE = W_A A \times W_P\ P \times W_Q\ Q.$

His approach is bounded with top managers' views (may vary) in selecting factors and lacks to reveal a standard approach.

(v) ***O****verall* ***I****nput* ***E****fficiency(OIE) and* ***T****otal* ***E****quipment* ***E****fficiency(TEE)*

Daniel Sheu (2006) stated that OEE is only half of the efficiency equation and proposed OIE to complete it. The true overall equipment efficiency is arrived at by multiplying OEE and OIE and named it as total equipment efficiency (TEE). He argued that even though output efficiency OEE may be same for two equipments they should not be judged as equal performers, as they may vary in consumption of inputs and named the common OEE as overall output efficiency (OOE). The author categorized the input resources as facilities/utilities, raw material, consumables/spares, manpower, non recurrent cost such as acquisition, training cost and maintenance tools. For calculating OIE non recurrent cost and maintenance tools are excluded and there is a relative weight associated with each input factor.

OIE $=\Sigma^{I}_{i=1} w_i e_i$ i = 1……I where I- input category, e_i- resource usage, w_i – relative weight of I.

$I_i = \Sigma^{I}_{i=1}$wi =1 and ei = D/A where D - theoretical ideal input resource level and A- actual resource input level..

$$TEE = OIE \times OOE = OIE \times OEE$$

III.(b) Equipment level –modification models (metric addition)

(i) ***O**verall **R**esource **E**ffectiveness(ORE)*

Eswaramurthi and Mohanram (2013) modified and expanded the concept of Daniel Sheu (2006) and postulated that "Overall Resource Effectiveness (ORE)" as the measure of overall effective time of the manufacturing system (resources). It is the product of Readiness (R), Availability of facility (Af), Changeover efficiency (C), Availability of material (Am), Availability of man power(Amp), Performance efficiency (P) and Quality rate (Q). ORE considers the facilities like man, machines, tools, jigs and fixtures and gauges and instruments

Readiness (R) $= \frac{plannedproductiontime}{totaltime}$ Availability of facility(Af) $= \frac{loadingtime}{plannedproductiontime}$

Changeover efficiency (C) $= \frac{operatingtime}{loadingtime}$ Availability of material (A_m) $= \frac{runningtime}{operatingtime}$

Availability of man power (A_{mp}) $= \frac{actual\ running\ time}{running\ time}$

Performance (P) $= \frac{Earned\ time}{actualrunning\ time}$ Quality rate (Q) $= \frac{quantityofpartsaccepted}{quantityofpartsproduced}$

ORE = R □□ Af□□ C □□ Am □□ Amp □□ P □□ Q □□ 100

(ii) ***O**verall **e**quipment and **e**nergy **e**fficiency(OEEE)*

JozefGlova (2012*)*,achieved OEE manipulations at par with Nakajima's concept as shown in figure and additionally added energy as key performance indicator apart from availability, performance and quality

OEEE = OEE×E.

III. FACTORY LEVEL –ALTERNATIVE MODELS

(i) ***O**verall **f**actory **e**ffectiveness(OFE)*

Scott and Pisa(1998), Oechsneret al.(2003), Williams(2006). This metric was developed to evaluate the factory level effectiveness. Researchers have different views and approaches and there is no common approach for this metric. According to Scott and Pisa (1998) OFE derives relationship among various machines and processes. It aims to integrate all possible activities and information of a production unit. The authors suggested to create a composite metric to achieve goals and applying weight factor for those metric is important.

(ii) ***O**verall **t**hroughout **e**ffectiveness(OTE)*

Haung et al. (2003*)* developed this metric on the basis of OEE dimensions for complex connected manufacturing systems. The manufacturing system may consist of predefined subsystem including series, parallel, assembly and expansion. Almost all industries may fall in any one these subsystems or configuration. The above developed metric is used in theoretical bottle neck detection.OTE is addressed as the theoretical efficiency and validated by simulation where, OTE derivation for series sub system having 'n' equipment, is

$$OTE^{(s)} = \frac{\min\left\{\begin{matrix}\min \\ i=1,2,.....n-1\end{matrix}\left\{OEE_{i} \times R_i \times \prod_{j=i+1}^{n} Qj\right\} OEEn \times R_n\right\}}{\begin{matrix}\min\{R_i\} \\ i=1,2,.....n\end{matrix}}$$

Ri is the theoretical processing rate of equipment specified by the manufacturer.
OEEi is the theoretical OEE of ith equipment
Qj is the quality efficiency of the jth equipment
In parallel sub system the author narrated there is no bottleneck equipment and calculated.OTE for this subsystem is also of theoretical efficiency and validated by simulation.

$$OTE^{(p)} = \frac{\sum_{i=1}^{n} (OEE_i \times R_i)}{\sum_{i=1}^{n} R_i}$$

Similar to parallel and series the OTE metric for assembly is also addressed as the theoretical efficiency and validated by simulation. The assembly system the author assumed with n upstream equipment and one assembly station and derived OTE metric as

$$OTE(a) = \frac{\min\left\{ \begin{matrix} \min \\ i = 1,2,....n \end{matrix} \left\{ OEEi \times \frac{Ri}{ki} \times Qn + 1 \right\} R_{n+1} \times OEE_{n+1} \right\}}{\min\left\{ \begin{matrix} \min \\ i = 1,2......n \end{matrix} \left\{ \frac{Ri}{ki} \right\}, R_{n+1} \right\}}$$

And finally the author derived the case of expansion sub system which consists of n downstream equipments and one expansion stations and queue capacity is unlimited. Moreover it is assumed that all equipments are independent. This is also addressed and validated as other subsystems. The OTE for this subsystem is

$$OTE(el) = \frac{\sum_{i=1}^{n} \min\{\mathrm{Re} \times OEEe \times K_i \times Q_i, R_i \times OEE_i\}}{\sum_{i=1}^{n} \min\{\mathrm{Re} \times k_i, R_i\}}$$

The developed metrics only aid equipments selection, factory layout design and detection of bottleneck theoretically and can be used only for diagnostic purpose. Computing metrics for continuous productivity is not proposed. In author view if series of metrics based on cycle time is developed more information regarding system performance can be obtained.

(iii) ***O****verall* ***A****sset* ***E****ffectiveness and (OAE) and* ***O****verall* ***P****roduction* ***e****ffectiveness (OPE)*

Haung and Muthiah (2008).These measurement tools are developed from OEE tool, to identify and to measure all losses in association with overall production process, and are widely applied in industries. Regarding industrial application these two terms mean the same but they differ in measuring elements or losses. In the calculation of OAE the maximum output is referred as theoretical maximum tonnage (T_T), production losses(PL) and the actual output as (T_{ACT}).as shown in figure 7. Therefore production loss is calculated as PL = T_T -T_{ACT} and OAE = $\frac{\mathrm{TACT}}{\mathrm{TT}}$. While considering OPE the losses are measured in terms of time losses. During OPE calculation it is assumed that the equipment is available 24×7 and the usage of time is measured almost similar to traditional OEE . In order to maximize OPE un scheduled time, scheduled down time and all production associated time losses(7 major losses) should be minimized as shown in figure 8

OPE $=\frac{valuableoperatingtime}{totalavailabletime}$

Thus OPE measures the effective utilization of manufacturing assets. Even though OAE and OPE have wider application in industries, they differ from one industry to another, because the elements or losses encountered during production differ. Specialized attention should be given for each element or loss and each may require different corrective action. Arriving at generalized model is the major drawback and moreover data collection will be too expensive (when ERP or MES used),if manually collected the accuracy will be very low.

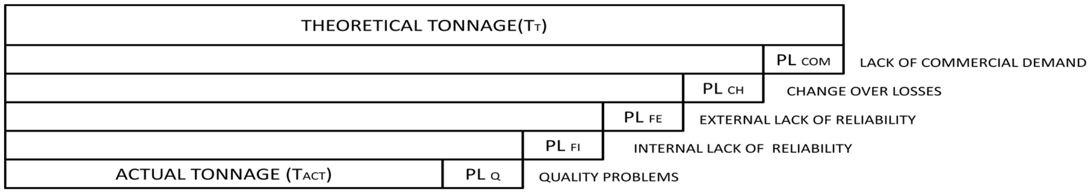

Figure 7. Overall asset effectiveness(OAE)

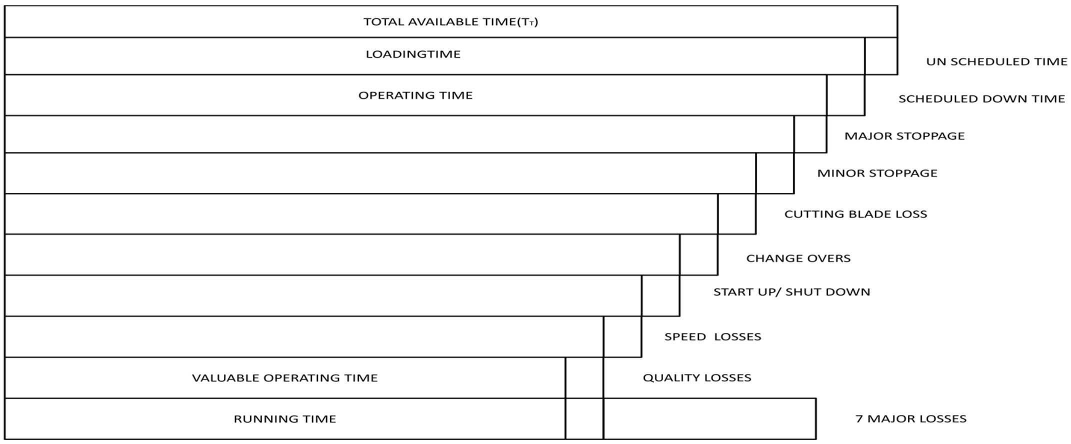

Figure 8. Overall production effectiveness(OPE)

IV. FACTORY LEVEL –MODIFICATION MODELS

In the context of modification in factory level classification OLE, OEEML and GPE were indexed.

(i) ***O**verall **L**ine **E**ffectiveness (OLE)*

Nachiappan and Anantharaman (2006) proposed an approach for continuous line manufacturing system consisting of 'n' number of machines. To extent OEE to factory level two thumb rules (simple average, product) which are in practice were considered and narrated their demerits. In the continuous product flow manufacturing system the output of process-1 will be the input for process -2. which in turn the operation time of the first machine will be the calendar time of second machine. This flow sequence is continuous for n processes. The defect and rework items are separated and only good items will be allowed to the next process. The authors clubbed the performance and quality dimensions and introduced a new term as line production quality performance efficiency (LPQP) as shown in (figure 9)

OLE = LA x LPQP

$LA = \frac{(OTn)}{LT} \times 100$ line availability efficiency (LA) is the operating time of nth machine (OT_n) expressed as a percentage of the loading time (LT).

$$LPQP = \frac{G_n \times Cyt_{BN}}{OT_1} \times 100$$

G_n – good parts produced by the last process and Cyt_{BN}– cycle time of the bottleneck machine.

OLE provides good results to a continuous product flow manufacturing, when all operations performed were strictly connected together. This approach does not allow decouplers or buffers between machines. If buffers are placed between machines OLE does not apply. Moreover both the dimensions LA and LPQP exclusively refer to the operating efficiency of last machine which misleads in identifying criticalities in the determination of bottleneck the authors utilized cycle time, whereas OEE of the machine also plays a vital role. The machine with highest cycle time in the manufacturing line should be treated as a key in the bottleneck determination. The major demerit is the key performance indicators of all the machines in the manufacturing line were not considered.

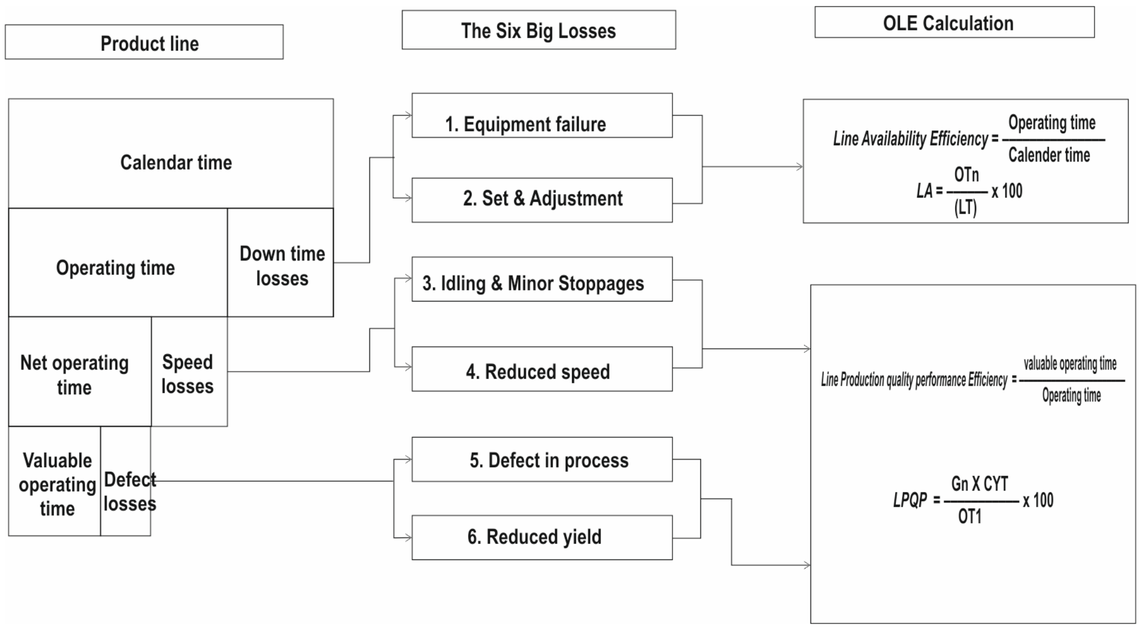

Figure 9. Overall line effectiveness (OLE)

*(ii) **O**verall **E**quipment **E**ffectiveness of a **m**anufacturing **l**ine (OEEML)*

Marcello Braglia (2008) is an integrated approach to assess performance of a production line even in the presence of buffers. This is the major advantage of this metric over OLE. The main causes of equipment dependent losses (EDL) and equipment independent losses (EIL) were considered. A structure of losses to calculate Total overall equipment effectiveness (TOEE)is shown in figure 10.

$$OEEML = \frac{Actual\ \text{Output}}{\text{Re}\ ference\ Output} = \frac{O_{LM}}{LLT\ /\ CT_{BN}}$$

O_{LM} - output released by the last machine.

OEEML is expressed as a function of the TOEE of the last machine

$$OEEML = \frac{MVT_{LM}\ /\ CT_{LM}}{LLT\ /\ CT_{BN}} = \frac{CT_{BN}}{CT_{LM}} \times TOEE_{LM}$$

TOEE is the product of availability loss due to planned maintenance (A_{PM}), availability loss due to machine's external factors(A_{ext}) and OEE's three dimensions.(A×P×Q)

$$TOEE = A_{PM} \times A_{ext} \times A \times P \times Q$$

$$= A_{PM} \times A_{ext} \times OEE$$

$$= A_{ext} \times OEEM$$

$$TOEE = \frac{Machine\ \text{valuable time}}{\text{Line loading time}}$$

Where TOEE is comprised of five independent factors.

$$TOEE = \frac{MLT}{LLT} \times \frac{MNLT}{MLT} \times \frac{MOT}{MNLT} \times \frac{MNOT}{MOT} \times \frac{MVT}{MNOT}$$

Machine loading time(MLT), Line loading time(LLT), Machine net loading time(MNLT) Machine operating time(MOT),Machine Net Operation Time(MNOT),Machine valuable time (MVT),Ideal cycle time of the bottleneck machine(CT_{BN})

The major advantage of OEEML is it suits even in presence of buffers. The author assumed ideal machines are on line and lack in the case of real production scenario.

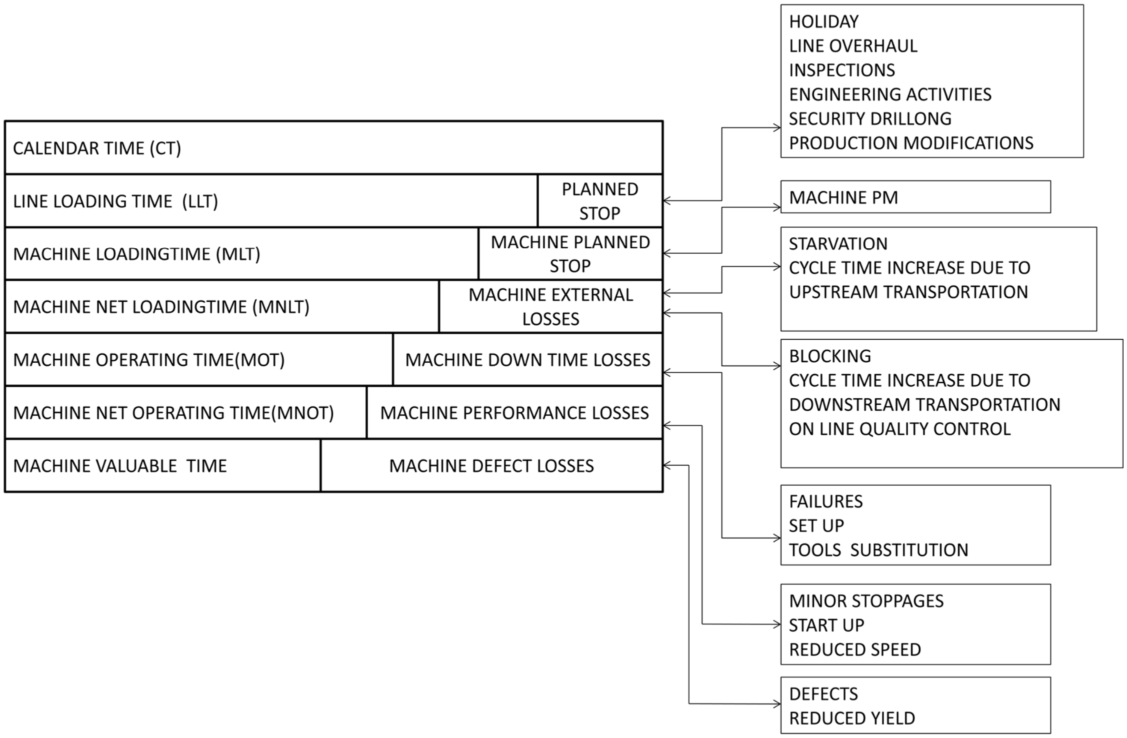

Figure 10 TOEE- Structure of losses.

(iii) ***G****lobal* ***P****roduction* ***E****ffectiveness (GPE)*

Gisela.etal.(2013)based on OEE develops a theoretical measure which integrates the aspects of a globally distributed production system. In this article the author reviewed TEEP,OAE/OPE, OLE and OEEML and suggested a new metric GPE. In modeling GPE, manufacturing effectiveness(ME),sourcing effectiveness(SE), transportation effectiveness(TE), stock effectiveness(S_tE), personnel effectiveness(PE) are accounted and through combining these the author arrived at GPE. This approach is only a theoretical one and while implementation computational drawbacks may occur. In other words GPE fails in adaptability and flexibility and needs some dynamic methods to achieve.

V. CONCLUSION

The review indicates that OEE and its extension are used as an index to evaluate either the performance of particular equipment or a subsystem and there is a lack of standard method to evaluate the effectiveness of the entire system irrespective of configuration.

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