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Overall Equipment Effectiveness Measures of Engineering Production Systems

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ABSTRACT

Measuring the Overall Equipment Effectiveness (OEE) of an engineering production system is essential for numerous purposes including scheduling, capacity estimation, and budgeting. During last few decades, several performance measurement techniques are developed from the basic OEE structure and are being implemented in different manufacturing industries. These newly developed techniques have some advantages and deficiencies over one another. The objective of this research is to evaluate these performance measurement techniques and their industrial applications. Most of these performance measures evolved from the fundamental concept of OEE. This paper summarizes and compares these techniques from different theoretical and practical perspectives.

KEYWORDS: OEE measures, Review

INTRODUCTION

Industrial equipment are supposed to produce products with a desired capacity, which is not satisfied in many cases. The manufacturing equipment are needed to be kept idle for a variety of reasons, including machine setup, breakdown, maintenance and raw material supply delay. Moreover, due to machine or human errors the production system may not produce 100% quality products. As a result, the equipment and/or a production plants would have an efficiency less than a perfect situation. Gathering a clear idea about the overall efficiency of the equipment is necessary for estimation of production rate, plant capacity, resource allocation, budgeting and scheduling. The overall equipment effectiveness (OEE) is treated as a common measure which is evaluated and used in many industries. However, there are several different approaches for OEE measurements which are termed with different names.

Muchiri and Pintelon (2008) analyzed, 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. They discussed two examples of industrial applications of OEE in packaging industry and chemical processing company. On the other hand, Munteanu *et al.* (2010) presented some computing techniques for establishing and improving the OEE measures, which reflect the actual production process in the Romanian automotive industry. Dal *et al.* (2000) presented a practical analysis of operational performance measurement at Airbags International Ltd (AIL), a supplier of airbag safety devices to the automotive industry.

For evaluating the performance of cellular manufacturing systems, Sarker and Li (1998) proposed a new efficiency measure called alternative routing grouping (ARG) efficiency which eliminates some limitations of available grouping measures—grouping efficiency and grouping efficacy; and derived its desirable properties. Besides this, Sarker and Khan (2001) presented a comparison between existing grouping efficiency measures and a new weighted grouping efficiency measure, named "doubly weighted grouping efficiency" measure. The relative performance of this doubly weighted grouping efficiency measure is evaluated by Sarker (2001) with respect to other existing measures.

When several machines operate jointly in a manufacturing line, OEE alone is not sufficient to improve the performance of the system as a whole. Braglia *et al.* (2008) presented a new metric, overall equipment effectiveness of a manufacturing line (OEEML) to overcome this limitation. On the other hand, based on the classical OEE approach of the TPM concept Lanza *et al.* (2013) developed a theoretical measure named as global production effectiveness (GPE), which integrates all aspects of a globally distributed production system and transfers the idea of the overall plant availability to the global production network. Muthiah and Huang (2007) developed an overall throughput effectiveness (OTE) metric based on the idea of comparing actual productivity to maximum attainable productivity. They presented an application of OTE to wafer fab and glass manufacturing industries in order to identify the productivity, bottleneck and opportunities for improvement quantitatively. Later on, Muthiah *et al.* (2008) developed algorithms to automate the factory-level performance monitoring and diagnostics process using OTE. They applied their automated performance diagnostics algorithms in a glass manufacturing industry.

However, Ron and Rooda (2005, 2006) claimed that OEE includes some equipment-independent conditions, which may not be caused by the equipment but by the environment of the equipment. That is why, they defined a new performance measure—equipment effectiveness, *E*, which is related to equipment-dependent states only. This *E* includes only events that are caused by the equipment itself and does not depend upon utilization. They presented an application of this equipment effectiveness measure in a semiconductor industry. Samat *et al.* (2012) proposed a four-phase equipment performance and reliability (EPR) model for measuring maintenance performance based on machine effectiveness. The model is implemented in a semiconductor company.

Wudhikarn (2010) proposed rank-order centroid (ROC) method to identify dissimilarity in weighting each OEE element and thus improved the original OEE. This newly calculating methodology is called as overall weighting equipment effectiveness (WOEE). He presented an application of WOEE in a fiber cement roof manufacturing company. Wudhikarn (2012) also developed another method named as overall equipment and quality cost loss (OEQCL) by adding the loss from cost of quality. This method eliminates some of OEE's weaknesses and expands its scope. Zammori *et al.* (2010) noted that OEE only provides a static representation of a process, and it fails to capture the real variability of its performances. In order to capture the stochastic nature of OEE, they presented an approximated procedure to generate probability density function of OEE. Yuniawan *et al.* (2013) proposed a new procedure to obtain the weights needed for measuring Weighted OEE, by a combined result of simulation and experiment, through the Taguchi method.

The performance measurement techniques and their applications discussed in the above literature survey are summarized in Table 1. Among the surveyed literature it is found that OEE is applied in packaging and chemical processing, automotive as well as (but not limited to) airbags manufacturing industries. Some applications of weighted OEE are found in the fiber cement, waterproofing coatings and crimping manufacturing Lines. On the other hand, some other performance measurement techniques like OAE, OPE, OEEML, and EPR are also reported to be applied in the packaging and chemical processing, automotive, glass and semiconductor manufacturing industries.

Table 1: Production line performance measures and their applications

Reference	Performance measures	Application area
Muchiri and Pintelon (2008)	Overall equipment effectiveness (OEE), Overall asset effectiveness (OAE), Overall plant effectiveness (OPE)	Packaging and chemical processing
Munteanu *et al.* (2010)	Overall equipment effectiveness (OEE)	Romanian automotive
Dal *et al.* (2000)	Overall equipment effectiveness (OEE)	Airbags International Ltd.
Sarker and Li (1998), Sarker and Khan (2001), Sarker (2001)	Doubly weighted grouping efficiency	Cellular manufacturing systems
Braglia *et al.* (2008)	Overall equipment effectiveness of a manufacturing line (OEEML)	Automotive firm—motor basement
Lanza *et al.* (2013)	Global production effectiveness (GPE)	Global manufacturing system
Muthiah and Huang (2007), Muthiah *et al.* (2008)	Overall throughput effectiveness (OTE)	Wafer fab and glass
Ron and Rooda (2005, 2006)	Equipment effectiveness, *E*	Semiconductor
Samat *et al.* (2012)	Equipment performance and reliability (EPR) model	Semiconductor
Wudhikarn (2010)	Rank-order centroid (ROC) method in overall weighting equipment effectiveness (WOEE)	Fiber cement roof
Wudhikarn (2012)	Overall equipment and quality cost loss (OEQCL)	Fiber cement
Zammori *et al.* (2010)	Generate probability density function of OEE	Waterproofing coatings
Yuniawan *et al.* (2013)	Taguchi method in weighted OEE	Crimping manufacturing Line

The literature survey reveals that same performance measures may be implemented in different type of industries and vice versa. However, a complete summary of the applications and the relationship between different performance measures still need careful attention for extensive research. Thus the objective of this research is to investigate the applications, implications and limitations, in addition to conduct a comparative study among different performance measuring approaches of a manufacturing system, which are evolved from the basic OEE tools. This research is expected to be helpful for the industrial personnel in finding the best way of measuring the overall performance of their production system.

BASIC CONCEPT OF OEE

The concept of OEE was first introduced by Nakajima (1988) as a tool for assessing the success of TPM philosophy. This OEE is based on three main elements which concern with different type of loss. These are, availability rate (*A*), performance efficiency (*P*) and quality rate (*Q*). These elements are determined as *A*= operating time/ loading time, *P* = net operating time / operating time and *Q* = (processed amount – defect amount)/ processed amount. Thus, OEE is the combined effect of these elements, expressed as $OEE = A\,P\,Q$.

Based on this fundamental idea, several other performance measures are evolved and applied in different industrial sectors. Some of those newly developed measures use different weighted factors of A, P and Q, whereas others use monetary factors to evaluate overall effectiveness of the manufacturing plant, line or equipment. The following section discusses these ideas elaborately.

OTHER EFFICIENCY MEASURES

Besides the fundamental idea of OEE, several modified versions of overall effectiveness measures are presented in different articles. Among those ideas, the weighted OEE, stochastic OEE, overall equipment and quality cost loss (OEQCL) are widely applied in engineering production systems.

Weighted OEE

Many researchers disagree with the way of Nakajima (1988) to calculate OEE because of some concrete limitations in the basic OEE. One of the noticeable limitations of traditional OEE is concerned in specifying the weights for each elements (availability, performance and quality) equivalently. Raouf (1994) argued that the characteristics of these elementary loss are totally different. So these should not carry the same weights. He proposed a modified OEE. In his methodology he assigned weights to all the elements using analytical hierarchy process (AHP). In this case, the weighted OEE (termed as PEE) is calculated as

$$PEE = A^{w_1} P^{w_2} Q^{w_3}\,, \tag{1}$$

where weights of A, P and Q are $w_1,\ w_2,\ w_3$ respectively such that $0 \le w_i \le 1$ and $\sum_i^3 w_i = 1$.

Raouf (1994) did not provide clear explanation how to calculate the values for w_i. Wudhikarn (2010) claimed that applying AHP for weight setting is complicated for the decision makers. His proposed methodology was aimed to rectify the weight setting of the weighted OEE's elements. He proposed another alternative simpler weighting method. He used rank-order centroid (ROC) methodology to determine the weights for the weighted OEE method. This technique transforms the swing ranks into the swing weights. The calculating formula of the ROC is defined as

$$w_i = \frac{1}{k}\sum_{j=i}^{k}\frac{1}{r_j}\,, \tag{2}$$

where r_j is the rank of the j^{th} element, *k* is the total number of the elements, and w_i is the normalized approximate ratio scale weight of the i^{th} element. Now, the weight of each element is specified by using the ROC method as illustrated in the Eq. (2). Thus, the overall weighting equipment effectiveness (WOEE) is calculated as

$$WOEE = w_1 A + w_2 P + w_3 Q \tag{3}$$

Wudikarn (2010) suggested that the machine with lowest OEE should be primarily selected for improving. However, some other research highlighted that the machine with lowest OEE may not have the highest loss while all equal weights for the elements of OEE do not mean the same loss.

Since several researches on OEE improvement faced difficulty when determining the proper weights, Yuniawan *et al.* (2013) proposed a new procedure to cover this drawback. They used simulation and statistical experiments in their research through Taguchi method. Usually Taguchi method is used as an optimization tool but it can statistically measure the relative sensitivity factor of OEE elements caused by different level values. To demonstrate the methodology Yuniawan *et al.* (2013) used a simulation software to obtain the results using Taguchi method. This proposed method was termed as simulation–Taguchi procedure (STP). This technique particularly makes it easier to define performance efficiency since it reflects the maximum capacity of the machine. The simulation consisted of three control factors (availability, performance and quality) using three levels of variations at each of the control factors. All variation levels used triangular random distribution to make it easier to define where the random failure would occur. Each experiment simulation runs 10 replications with each control factor variation parameter level.

Taguchi method usually defines the uncontrollable (noise) factors in an experiment. This method provides signal-to-noise (S/N) ratio calculation in the experiment. The S/N ratio is a measure of the impact of noise factors on performance. The delta (Δ) values are calculated from the differences between maximum and minimum value of S/N ratio for each level of control factors. Finally a simple mathematical equation was used as

$$w_i = \frac{\Delta_i}{\sum_{i=1}^{3} \Delta_i} \quad (4)$$

to obtain the weights. Here Δ_i for i = 1, 2 and 3 are the delta-values for Availability, Performance and Quality respectively. Yuniawan *et al.* (2013) suggested that the same procedures can be used to calculate the weights for the elements in WOEE and PEE as well. It can be objected that STP seems to be difficult to implement. Moreover, obvious and sufficient data are needed to consider while making decisions for the improvement.

The weighted OEE concepts listed above notify that, a concrete direction of choosing a suitable weighted method is not available. Though several researches including Raouf (1994), Wudhikarn (2010) and Yuniawan *et al.* (2013) are reported where weighted method succeeded over the basic OEE concept while implemented in different industrial areas, these weighted OEE measures cannot deal with the stochastic nature of the performance of an equipment or a production plant.

Stochastic OEE

Zammori *et al.* (2011) noticed that deterministic OEE fails to capture the real variability of manufacturing performances. Variability affects work in process and queuing time and makes the time loss uncertain hence creates the possibility of hidden loss. To deal with this stochastic nature of OEE, Zammori *et al.* (2011) proposed an approximated procedure based on the application of the central limit theorem (CLT).

The basic idea of this stochastic OEE is to describe each time loss, T_i by means of a beta distribution. Then CLT is implemented to find the gap between the opening time (*OT*) and the net loading time (*NLT*) which is denoted by G_N and the gap between the *NLT* and the valuable time (*VT*) denoted by G_V. Though both G_N and G_V are independent beta random variables, the CLT assures that both G_N and G_V tend to be normally distributed, with mean and variance given by the following expressions respectively: $G_N \sim N\left(\sum_i \mu_i, \sum_i \sigma_i^2\right)$ and $G_V \sim N\left(\sum_j \mu_j, \sum_j \sigma_j^2\right)$, where i and j denote the number of time loss that belong to G_N and G_V, respectively, and μ, σ denote the mean and standard deviation of that time loss. So, by the definition *NLT* and that of *VT* the normality assumptions are preserved as

$$NLT = \left(OT - G_N\right) \sim N\left(OT - \sum_i \mu_i, \sum_i \sigma_i^2\right) \tag{5}$$

$$VT = \left(NLT - G_V\right) \sim N\left(OT - \sum_i \mu_i - \sum_j \mu_j, \sum_j \sigma_j^2 + \sum_i \sigma_i^2\right) \tag{6}$$

Now, OEE and its corresponding probability density function (pdf) can be obtained from the ratio of *VT* and *NLT*. As the ratio of two normal random variables does not preserve the normality, Zammori *et al.* (2011) suggested to obtain a standard normal approximation $P(OEE \le OEE_{critical})$ of the real probability density function of OEE as

$$P(OEE \le OEE_{critical}) = \Phi_{0,1}\left(\frac{\mu_L - \mu_V}{\sqrt{\sigma_L^2 + \sigma_V^2}}\right) \tag{7}$$

where, μ_L, σ_L are mean and standard deviation of loading time and μ_V, σ_V are mean and standard deviation of valuable time. Zammori *et al.* (2011) also presented a method to decide which corrective action should be deployed first among several potential corrective actions on OEE. To evaluate the potential effects in terms of both efficiency and effectiveness the percentage change in the mean and SD of the OEE is observed by the following expressions,

$$\eta_j = \frac{\hat{\mu}_{OEE_j} - \mu_{OEE_j}}{\mu_{OEE_j}} \text{ and } E_j = \frac{\hat{\sigma}_{OEE_j} - \sigma_{OEE_j}}{\sigma_{OEE_j}}, \tag{8}$$

where η is the efficiency and *E* is the effectiveness of the j^{th} corrective action. $\hat{\mu}_{OEE_j}$ and $\hat{\sigma}_{OEE_j}$ are mean and standard deviation of the new OEE obtained through the intended j^{th} corrective action. To estimate $\hat{\mu}_{OEE_j}$ and $\hat{\sigma}_{OEE_j}$ before the corrective action, a heuristic procedure was suggested which is valid for beta random variables. For doing so, the production engineers were asked to give a pessimistic and a reasonable evaluation of the obtainable reduction of the corresponding time loss. Finally, using the methodology described above, a new pdf of OEE_j was suggested to obtain. Now the easiest way to rank the solutions is to compare OEE_j with a critical value of the OEE and evaluate the probability of each j^{th} corrective action less than the critical OEE. The corrective action is chosen which gives the lowest value of probability.

The proposed approach induces some approximations; thus this approach does not give the exact pdf of OEE. Moreover, it was reported that the method is valid for values of OEE < 90% and when the variability of the equipment internal loss is high. However, this is a good approach indeed, because it allows to identify hidden loss and can estimate the impacts of potential corrective actions in terms of both efficiency and effectiveness.

Alternative to OEE Methods

The overall equipment effectiveness (OEE) and other adapted measures discussed above are not suitable for comparing among dissimilar type of machines those have different capacity and different process parameters such as production capacity, cost of material and quantity of the operator. To eliminate these problems Wudhikarn (2012) proposed a new computing methodology for estimating the quantitative loss in monetary units. This modified method is termed as overall equipment and quality cost loss (*OEQCL*). This method analyzes the loss into three elements of basic OEE approach, but the result is shown in monetary value. In addition to these basic elements, *OEQCL* also adds cost of quality (*COQ*). Thus it becomes

$$OEQCL = AL + PL + QL + COQL, \qquad (9)$$

where *AL* is the availability loss, *PL* is the performance loss, *QL* denotes the quality loss and *COQL* denotes the cost of quality loss. These are defined as $AL = OL_A + PCL_A$, where OL_A and PCL_A are respectively denoted for opportunity loss and production cost loss for availability rate element; and $PL = OL_P + PCL_P$, where OL_P and PCL_P are respectively denoted for the opportunity loss and production cost loss for performance efficiency element. On the other hand, the quality loss is expressed as

$$QL = \left(OL_{Q-rej} + DML_{Q-rej} + PCL_{Q-rej}\right) + \left(PCL_{Q-rew} + R_{wk}L_{Q-rew}\right) \qquad (10)$$

where, OL_{Q-rej} is the opportunity loss, DML_{Q-rej} is the direct material cost loss and PCL_{Q-rej} is the production cost loss for quality rate sub reject element except direct material cost loss; and PCL_{Q-rew} is the production cost loss for quality rate sub reject element except direct material cost loss and $R_{wk}L_{Q-rew}$ is rework loss. The cost of quality loss is expressed as $COQL = \Sigma CQP_i + \Sigma CQA_i$, where CQA_i is the actual cost of quality for the element i and CQP_i is the cost of quality of element i for production allocating method.

The applications of OEQCL reported by Wudhikarn (2012) shows that in some cases the machine with highest OEQCL also has the highest OEE. In order to implement this method of performance measure, both general cost accounting and cost of quality accounting need to be available completely.

A COMPARATIVE STUDY OF DIFFERENT MEASURES

From the discussion on available performance measures, it can be concluded that the fundamental approach of measuring OEE proposed by Nakajima (1988) considers equal weights to availability (*A*), performance (*P*) and quality (*Q*), which is not practical in many cases. This limitation is overcome by introducing weighted OEE. However, the exponentially weighted OEE method (Raouf, 1994) as well as the linearly weighted OEE method (Wudhikarn, 2010) do not provide a clear explanation how to determine the weights. Weights are mostly subjective in both of these two methods. Whereas, the simulation–Taguchi procedure (Yuniawan *et al.,* 2013) is more practical, because weights are set from statistical experiments. This method requires obvious and sufficient data while being implemented. None of the weighted OEE method can deal with the stochastic nature of OEE. This limitation of the basic and weighted OEE is overcome by the stochastic OEE approach by Zammori (2011), but this method provides an approximated pdf, not exact. On the other hand, Wudhikarn (2012) presented the quantitative loss in terms of monetary units, in his proposed method of performance measure named as, overall equipment and quality cost loss (OEQCL). The general cost accounting and the cost of quality accounting must be completely available for measuring OEQCL of a production system.

Table 2: Comparisons between the existing methods for calculating OEE

SL	Methodology	Author	OEE model	Advantages	Drawbacks
1	Basic OEE	Nakajima (1988)	$OEE = A\,P\,Q$	Fundamental approaches	Each elements are equally weighted.
2	Exponentially weighted OEE (PEE)	Raouf (1994)	† $PEE\|_{\text{AHP}} = A^{w_1} P^{w_2} Q^{w_3}$	Added exponential weighted factors	No clear explanation how to determine the weights. Weights are mostly subjective.
3	Overall weighting equipment effectiveness (WOEE)	Wudhikarn (2010)	‡ $WOEE\|_{\text{ROC}} = w_1 A + w_2 P + w_3 Q$	Added linear weights	Still cannot explain some case such as lowest OEE machine may not have the highest loss.
4	Simulation–Taguchi procedure (STP)	Yuniawan *et al.* (2013)	Uses simulation and statistical experiments through Taguchi method to obtain the weights.	More practical because weight is set from statistical experiments	Difficult to implement. Obvious and sufficient data have to be available.
5	Stochastic OEE	Zammori (2011)	$P(OEE \le OEE_{critical}) = \Phi_{0,1}\left(\frac{\mu_L - \mu_V}{\sqrt{\sigma_L^2 + \sigma_V^2}}\right)$	Can deal with both efficiency and Effectiveness	Approximated pdf, not exact.
6	Overall equipment and quality cost loss (*OEQCL*)	Wudhikarn (2012)	$OEQCL = AL + PL + QL + COQL$	Quantitative losses presented in terms of monetary unit	General cost accounting and cost of quality accounting must be completely available.

†*Weights* determined by AHP methodology, ‡ *Weights* determined by rank-order centroid (ROC) methodology

CONCLUSION

For numerous reasons the performance of a manufacturing system is required to be measured. The purpose of the performance measure includes scheduling, job sequencing, capacity estimation and budgeting. Overall equipment effectiveness (OEE) is a well-known basic concept of performance measure. Due to some limitations several modifications on OEE are proposed and implemented during last few decades. This research focuses on the evolution of OEE measurement concepts and their applications in engineering production systems. A critical review on different effectiveness measures are presented here along with the advantages and limitations of those measures.

In many manufacturing systems the performance are measured by assigning equal weights to all affecting factors (availability, performance and quality). In those cases a basic OEE measure can be enough to deliver necessary information. However, exponential or linear weights can be assigned to the factors depending on the system behavior. The weights can be obtained by AHP, rank-order centroid methodology or statistical experiments. On the other hand, the stochastic OEE is considered for finding the approximate probability density function of OEE if the parameters or factors are highly probabilistic in nature. If the general cost accounting and the cost of quality accounting are available, an overall equipment and quality cost loss (*OEQCL*) can be evaluated in terms of monetary values. Based on these concluding remarks this survey paper can be treated as a guideline for selecting a suitable performance measurement tool among the existing approaches or developing an appropriate performance measurement technique for a particular type of production system or equipment.

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