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# SMART OEE-SIGMA MODEL FOR PRODUCTION PROCESS OPTIMIZATION

*Abstract: The quest for effective utilization of both humans and machinery is on the increase in order to survive competition. Overall Equipment Effectiveness (OEE) metric application in industry has been facing a challenge of continuing advancement in industrial operations. A smart OEE is required for a quick response to the dynamism in industrial system. In this study, OEE metric is made smart by integrating sigma continuous improvement tool into it for the enhancement of dynamism required of the traditional OEE model measured basically on three factors-availability, performance and quality. System productivity dynamism is measured and predicted through sigma statistical variation of the production process defined as a ratio of delivered output (supply) to the expected (planned) output. The model was applied to a production process of fast moving product. The results obtained for the seven consecutive years (2006 to 2013) for traditional OEE are 100%, 92%, 84%, 86%, 89%, 81%, and 84%, respectively. In the new OEE-Sigma method, productivity can be continuously improved over the years by at most 77%. This indicated that smart OEE-sigma model is a better tool for enhancing continuous improvement in a dynamical processing environment.*
*Key words: Smart OEE, Sigma metric, continuous improvement, production process*

**Pametan OEE-sigma model za optimizaciju procesa proizvodnje.** *Potraga za efikasnom upotrebom kako ljudi tako i mašina je u porastu kako bi preživeli konkurenciju. Primena metričkih efekata na ukupnu efikasnost opreme (OEE) u industriji je pred izazovom stalnog napretka industrijskih operacija. Pametni OEE je potreban za brz odgovor na dinamiku u industrijskom sistemu. U ovoj studiji, OEE metrika je napravljena pametnom integracijom sigma kontinuinualnog alata za poboljšanje njega kao i poboljšanje dinamičnosti koja se zahteva od tradicionalnog OEE modela koji se meri u osnovi na tri faktora - dostupnost, performanse i kvalitet. Dinamika produktivnosti sistema se meri i predviđa sigma statističkom varijacijom proizvodnog procesa definisanog kao odnos isporučene proizvodnje (ponude) i očekivanog (planiranog) izlaza. Model je primenjen u procesu proizvodnje proizvoda koji se brzo kreće. Dobijeni rezultati za sedam uzastopnih godina (od 2006. do 2013. godine) za tradicionalne OEE su 100%, 92%, 84%, 86%, 89%, 81% i 84%, respektivno. U novoj OEE-Sigma metodi, produktivnost se može kontinuirano poboljšavati tokom godina za najviše 77%. Ovo je pokazalo da je pametni OEE-sigma model bolji alat za poboljšanje kontinualnog poboljšanja u dinamičkom okruženju za obradu.*
*Ključne reči: Smart OEE, Sigma metrika, kontinualno poboljšanje, proizvodni proces*

## 1. INTRODUCTION

One crucial area that every plant can improve upon is efficiency. One of the best measures of efficiency is Overall Equipment Effectiveness (OEE) [1]. Overall Equipment Effectiveness (OEE) is a widely used performance indicator in manufacturing industries around the world [2]. It was initiated when Nakajima [3] introduced the Total Productive Maintenance (TPM) concept where the main goal is to improve and sustain equipment efficiency. Most of the researches involving the OEE focused on the areas of maintenance, performance and productivity improvements. The increasing digitalization of industry provides means to automatically acquire and analyze manufacturing data [4]. Consequently, companies are investing in Manufacturing Execution Systems (MES) where the OEE measure is a central and important reason for the investment [4]. The validity and usefulness of OEE measures are highly dependent on the nature or authenticity of data collected.

The aim of this study is to develop a smart OEE-Sigma model for manufacturing process optimisation under a dynamic and competitive environment. The stated aim was achieved by: identifying and integrating relevant parameters of the Overall Equipment Effectiveness (OEE) metrics; and creating a smart continuous improvement environment for the process. Traditional OEE metrics considered only three principal factors-availability; performance and quality of the production process [5, 6, 7], and the evaluation procedure is static. There is the need to go in-depth and include element of dynamism into the traditional OEE metric to enable sustainable productivity in the production system. The use of statistics based on sigma variation metric as improvement tool is recently gaining ground in the manufacturing system, but not yet popular in the OEE measures. In this study integration of Sigma tool into the OEE metrics is enabled to enhance Overall Process Improvement (OPI) in a production system. Sigma statistic varies from the least of one-, to the highest (precision) of six-sigma. Six sigma statistics provides improvement probability (0.9999934) close to unity (1) [8].

Six sigma as an arm of lean concept, and it is a useful tool for measuring, monitoring and controlling

the process variations towards continuous improvement attainment in a manufacturing process. Distinction between six sigma and lean system according to Michael [8] is that while six-sigma focuses on reducing process variation and enhancing process control, the lean system seeks to eliminate or reduce wastes (non-value –added) using team work, clean, organized and well-marked work spaces. Lean and six-sigma have same general purpose of providing the customer with the best possible quality, cost, delivery and a newer attribute. Lean achieves its goal by using philosophical tools such as Kaizen, workplace organization (5S) and visual controls, while six-sigma is based on statistical analysis. This study will develop hybrid tool (OEE-Sigma) that can be applied in production process as continuous improvement tool.

The improvements (by reducing losses) obtained by implementing JIT strategy can be represented (in quantitative term) using sigma quality improvement statistics (for variation reduction). Six sigma tool is recently introduced into lean manufacturing strategy to answer the question of which process (resource) can be classified under black-belt and green-belt based on the level of productivity enhancement. Evidence of integrating the six sigma tool into OEE metric was found scanty in the previous studies. Formulation of a smart OEE model using sigma metric as improvement tool will break a new ground in the lean manufacturing research in changing industrial environment. The present state of art is presented in section 2, methods of approach are formulated in section 3, section 4 discusses results obtained by case study, and conclusions are enumerated in last section 5.

## 2. PRESENT STATE OF ART

OEE measure metrics in the past studies and their weaknesses are presented as follows. Kunsch et al. [9] utilized regression models/generalized linear models to relate three factors of OEE (availability, performance, and quality efficiency) in order to optimize one factor over the other using response surface methodology. In the model, new input to the traditional OEE factors was not identified. The use of a Multidimensional view of Technology (AMT) in OEE measure by Swamidassa and Kothab [10] has directly imparted improvement only on large scale firm. No tangible impact was found with small scale firms, which were the bases of industrial development. Ljungberg [11] did a good work by identifying the three critical factors-availability, performance and quality affecting OEE, but failed to consider process dynamism and prediction of major drivers of the overall equipment effectiveness. Hansen [12] in his study elucidated the efficacy of OEE measure as powerful production/maintenance tool for increased profits. Productivity cannot lead to profitability without the consideration of production dynamism in OEE metric. Lean bundle contribution on firm performance proposed by Shah and Ward [13], was supportive to plant size on lean implementation but less supportive to unionization and plant age which traditional OEE measures can sustain. This study neglected improvement measure based on sigma

statistics. Braglia et al. [14] established OEEML as a new form of OEE metric in an attempt to overcome a limitation of individual equipment over jointly operated machines, with the inclusion of an integrated approach to assess the performance of a Manufacturing Line (ML). The model is found wanting in explaining the extent at which the effectiveness is supported by in-process inventory.

Wilson [15] based the measure of OEE on the three traditional factors- availability, performance and quality efficiencies, but neglected the issue of sigma statistic variation in production process. From the work of Almeanazel [16], deployment of traditional OEE metrics in a steel company enabled the realization of 99% in quality factor, 76% in availability factor, and 72% in performance efficiency. Improvement tools such as SMED, Computer Maintenance Management System (CMMS) and Production Planning (PP) were suggested to the company to apply, whose practical implementation was not provided. Garza-Reyes et al. [17] analyzed the relationship between OEE and Process Capability (PC) measures using a bottling line, through which a cutoff point of 1.33 capability indices (CI) instead of popular 1.0, was realized, where further improvements in PC will have little or no impact on OEE. The study challenged traditional prevailing knowledge of considering value of 1.0 as the best PC target in terms of OEE. It can be concluded from the study that OEE can be greater than 1.0 when measured in term of capability indices. However, OEE greater than 1.0 will not be expected in lean manufacturing environment where the production systems are being managed based on demands.

Madhavan et al. [18] in his study reiterated the three conventional factors stated by Ljungberg [11] without considering other factors that affect process demand (plan) and supply (deliver). Zuashkiani et al. [19]'s study addressed the challenge of variation of OEE across firms by creating a system of understanding dynamic processes that control the evolution of OEE through time. Action taken to fix problems (reactive maintenance, poor morale and fire-fighting) in the short run will erode the capability of the organization over the long run, and can lead to lower OEE. Risk of encountering the stated production challenges can be transferred to appropriate/relevant experts in the production cycle by adopting good supply (demand) prediction scheme to sustain OEE and then enhance productivity.

Static nature of evaluating OEE in the past needs improvement to reflect realistic and dynamic nature of production environment by developing suitable heuristics with relevant continuous improvement parameters under the application of structured continuous improvement tools (Kaizen, system standardization (5S), Just-in-Time (JIT), and Single Minute Exchange of Die (SMED)). This is realizable by integrating OEE and sigma metrics to enable statistical process variation measurement and improvement to be carried out under application of relevant modelling approach. From the foregoing, it is crystal clear that most of the past studies considered and analyzed only traditional OEE factors in isolation.

This study will address OEE factors separately and in combination by holistically integrating them at improving the system performance using sigma metric approach in the presence of tractable process supply and demand prediction scheme.

## 3. METHOD OF APPROACH

The proposed integration of OEE factors (quality, performance and availability) as related to the processing floor is shown in Fig. 1. As shown in the figure, all the OEE factors are interrelated. Improved performance is achievable when the equipment availability, process performance and product quality are highly efficient.
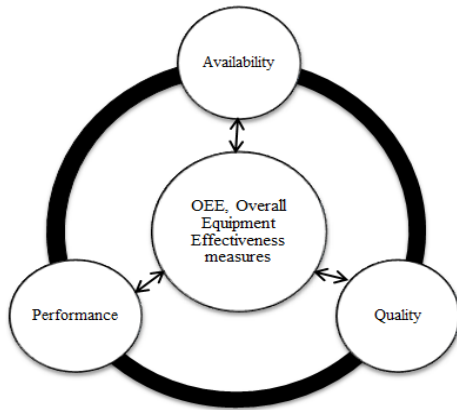


Fig. 1. Overall equipment effectiveness integration

The stated factors are contributory to the overall equipment effectiveness measures. The system integration revealed that lapse (weakness) in an OEE factor will have multiplication effect on the other OEE factors leading to reduction in OEE performance. The stated interrelationships can be represented as a function given by Eqn 1.

$$OEE = f(Availability, \alpha; Performance, \beta; Quality, \mu) \quad (1)$$

For a production process equipment availability may be good or poor, performance of the system may be good or low and quality of process may be good or bad. The productivity level of the production system can be determined based on the OEE relationship given in Eqn. 1. The OEE factors, as stated, demonstrated a multiplying effect [20]. It is inferable that an industrial plant with OEE greater than 0.5 (50%) is sustainable [11]. In order to operate a sustainable OEE in the manufacturing system each factor should set at a minimum of 0.8 (80%) efficiency for attaining a multiplying effect of OEE leading to minimum OEE value of 0.5 (OEE≥ 0.5). OEE of 0.5 is set to be minimum effectiveness value required of a production process to succeed. A shortfall below 0.5 is an indication of poor performance, which calls for proactive corrective measures to normalize the situation.

A good measure of OEE in a production process is based on simple ratio of output delivered (supply) to the expected (demanded) output. On this basis, tools that can measure statistical variation on the two (delivered and expected) outputs will be applicable and useful in evaluating individual and combined OEE factors. It is therefore reasonable seeking continuous improvement strategy through application of sigma metric tool ($\sigma$) due to its ability to handle process variation. At this end, a methodology that can help to measure continuous improvement in OEE under changing behaviour of the production system (OEE-Sigma metrics) is proposed with the following guiding equations (Fig. 2).

If,

$OEE - Sigma \geq 1$, stop, improvement is satisfactory

$0 \leq OEE - Sigma \prec 0$, otherwise, continue $\quad$ (2)

$OEE - Sigma\_error = 1 - f(OEE - Sigma)(1 - \sigma)^x \quad (3)$

$OEE - Sigma\_error$ is obtainable using Eqn. 3 based on iterative results from Eqn. 2. $f(OEE - Sigma)$ and $\sigma$ are the combined $OEE - Sigma$ ($OEE'$) output and improvement factor, respectively obtained from the process improvement at given time, $x$. From Eqns (2) and (3), it is realizable that the system should be continuously improved over time $x$ until the set target is met (that is $OEE \geq 1$), when the error is moving to zero value.
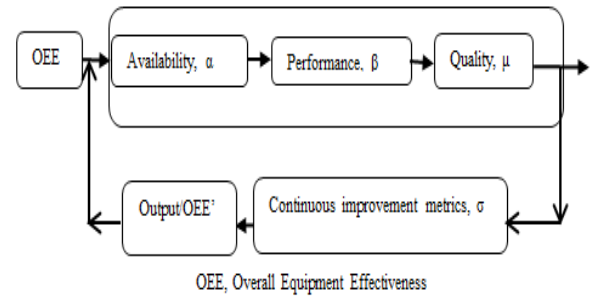


Fig. 2. System continuous improvement framework

## 4. FORMULATION OF OEE SIGMA MODEL

The product equation for the Overall Equipment Effectiveness (OEE) measures given by Bruce [1] and Dilworth [20] is expressed as,

$$OEE = \alpha.\beta.\mu \quad (4)$$

where:

α, is the availability efficiency of a production equipment

β, is the performance efficiency of the equipment

μ, is the quality rate (efficiency) of products (output)

Dynamic sub-models for evaluating productivity contributions of each of the OEE factors as related to production process are developed as follows:

System Availability, ($\alpha$). This is determined as the ratio of actual (delivered) production volume per unit time and the planned (expected) production volume per unit time.

$$\alpha = \frac{t_1}{t_2} = \frac{Delivered \ production \ volume \ / unit \ time}{Expected \ production \ volume \ / unit \ time} \quad (5)$$

Dynamism in $\alpha$ is represented by $\alpha'$ and is motivated by improvement factor, $sigma, \sigma$ in equipment availability at time $x$ as given in Eqn. (6);

$$\alpha' = f(\alpha)(1+\sigma)^x \qquad (6)$$

If $\left[ \begin{array}{l} \alpha^1 \geq 1, stop, equipment, satisfactory \\ 0 \leq \alpha^1 < 1, otherwise, continue \end{array} \right. \qquad (7)$

System Performance, ($\beta$) is measured as the system performance delivered (in %) per unit time ($t_0$) over the system performance expected (in %) per unit time ($t_n$), as shown in Eqn. 8

$$\beta = \frac{t_0}{t_n} = \frac{System\ performance\ delivered(\%)/unit\ time}{System\ performance\ \exp ected(\%)} \qquad (8)$$

Similarly,

$$\beta' = f(\beta)(1+\sigma)^x \qquad (9)$$

Then,

If $\left[ \begin{array}{l} \beta^1 \geq 1, stop, performance, satisfactory \\ 0 \leq \beta^1 < 1, otherwise, continue \end{array} \right. \qquad (10)$

System Quality, ($\mu$) is measured by calculating the quality products delivered, $G$ (in %), is obtained by subtracting rejected/rework pieces from total quantity produced) over the total quantity produced, $G_p$ (in %).

$$\mu = \frac{G}{G_p} = \frac{Quality\ products\ delivered(\%)/unit\ time}{Quantity\ produced(\%)} \qquad (11)$$

Similarly, system quality dynamism can be represented by,

$$\mu' = f(\mu)(1+\sigma)^x \qquad (12)$$

And the corresponding dynamic process constraint is given as,

If $\left[ \begin{array}{l} \mu^1 \geq 1, stop, quality, satisfactory \\ 0 \leq \mu^1 < 1, otherwise, continue \end{array} \right. \qquad (13)$

Eqn. 4 can be used to determine OEE after which optimality of the process can be dynamically obtained using Eqns 2 and 3. Introduction of sigma improvement metric ($\sigma$) into the OEE model will yield improved optimality model given in Eqn. 22. Optimal search was carried out in OEE' based on the dynamism in the integrated sigma metric tool.

$$O\dot{E}\dot{E} = f(\alpha)(1+\sigma)^x . f(\beta)(1+\sigma)^x . f(\mu)(1+\sigma)^x \qquad (14)$$

The summary of the model is stated as follows.

Optimise $OEE'$ (Eqn. 14)

Subject to the following constraints:

System availability $\alpha'$ (Eqn. 7)

System performance $\beta'$ (Eqn. 10)

System quality $\mu'$ (Eqn. 13)

Non-negativity constraints:

$f(\alpha), f(\beta), F(\mu) \geq 0$

The model as stated is a constrained linear/nonlinear programming model which is solvable using analytical approach and excel tools.

## 5. ANALYSIS OF MODEL PARAMETERS

The stated performance functions; $f(\alpha)$, $f(\beta)$, $f(\mu)$ were analyzed based on the past data of production output parameters, $t_1, t_2,$ $t_0,$ $t_n, G,$ $G_p$, designated as output (dependent) variables, y and independent time variable, x using regression models (which can be either linear or nonlinear in nature), and the efficient model can be chosen based on the emerged highest coefficient of determination $R^2$. $R^2$ performance measure was used because of its popularity in determining the degree of correlation of engineering related data [21, 22]. Trend line options were checked to find the line of best fits using exponential, linear, logarithmic, polynomial and power regression equations, as the most commonly used models [22] with their respective regression coefficients. The best regression models were used for determining performance ratios of individual output, from which OEE and OEE' were evaluated using Eqns. (4) and (14), respectively.

The errors of meeting the target (1 or 100%) were evaluated using Eqn. (2). Non-meeting the target (errors that are more than zero) required introduction of sigma metrics, $\alpha$ as improvement tool. Introduction of $\alpha$ is a continuous improvement factor on $OEE'$ (Eqn. 14). The value of $\alpha$ is based on the outcome of team of experts statistical variation analysis of process demand and supply which dependent on Total Productive Maintenance (TPM). The improvement attainable in productivity measure may fall under any of the following statistical standards of $\alpha$ metrics; one-, two-, three-, four-, five-, or six-sigma [23]. Six-sigma is the highest factor of variation reduction (from target, 1) attainable, and the error is very close to zero (0.0000034), making it a good replacement for the costly 100% inspection strategy, popularly known as jidoka in Japaness language [15, 23].

## 6. PROCESS TESTING AND VALIDATION

The relevant data (related to productivity performance of the OEE factors) covering eight (8) years (2006-2013) collected from a production floor are given in Tables 1-3. The last columns of Tables 1-3 show the ratios that indicate the performance for the years under review (obtained using Eqns. 5, 8, and 11). The best outcomes of the respective performance (prediction) functions $f(\alpha), f(\beta), f(\mu),$ obtained using excel tools are presented in Table 4. The best regression equations was chosen based on highest $R^2$ value, to produce the best prediction results for system availability, $f(\alpha)$, system performance, $f(\beta)$, and system quality, $f(\mu)$, on the bases of process delivered (supplied) and expected (demanded), respectively. The corresponding $OEE'$ results are respectively presented in Table 5.

| Year | Expected Production Volume (million) | Production Volume Delivered (million) | Ratio (α) |
|---|---|---|---|
| 2006 | 10,011.00 | 11,211.17 | 1.0 |
| 2007 | 13,541.26 | 13,541.26 | 1.0 |
| 2008 | 15,096.49 | 14,593.49 | 0.97 |
| 2009 | 14,281.36 | 16,290.13 | 1.0 |
| 2010 | 16,035.19 | 18,058.25 | 1.0 |
| 2011 | 18,996.82 | 18,499.26 | 0.97 |
| 2012 | 19,736.88 | 19,298.22 | 0.98 |
| 2013 | 20,808.32 | 20,341.56 | 0.98 |
| 2014 | 22,909.26 | 20,552.13 | 0.90 |

Table 1. System Availability Data

| Years | Performance Expected (%) | Performance Delivered (%) | Ratio (β) |
|---|---|---|---|
| 2006 | 90.00 | 90.00 | 1.00 |
| 2007 | 91.00 | 91.00 | 1.00 |
| 2008 | 91.50 | 80.00 | 0.87 |
| 2009 | 91.50 | 79.00 | 0.86 |
| 2010 | 92.00 | 82.00 | 0.89 |
| 2011 | 92.00 | 77.00 | 0.84 |
| 2012 | 92.50 | 80.00 | 0.86 |
| 2013 | 92.50 | 82.00 | 0.89 |

Table 2. System Performance Data

| Year under review | Quality Product Delivered (%) | Quality Product Expected (%) | Ratio (μ) |
|---|---|---|---|
| 2006 | 75.00 | 77.00 | 0.97 |
| 2007 | 76.00 | 70.00 | 1.0 |
| 2008 | 77.00 | 79.00 | 0.98 |
| 2009 | 77.00 | 79.50 | 0.97 |
| 2010 | 78.00 | 81.00 | 0.96 |
| 2011 | 78.50 | 81.00 | 0.97 |
| 2012 | 79.00 | 81.20 | 0.97 |
| 2013 | 80.00 | 81.21 | 0.99 |

Table 3. System Quality Data

# 7. PROCESS EFFECTIVENSS EVALUATION

The prediction results (Tables 4 and 5) generally showed that the OEE of the plant was varying throughout the years under review. OEE (1.0) in 2006 decreased to 0.81 in 2011. OEE increased steadily after 2012. OEE outcomes were majorly less than unity. This is a concern that calls for improvement. Validation of the results with $R^2$ value close to unity indicated that the predicted OEE factors were accurately representing the production floor data presented in Tables 1-3. These outcomes have qualified the established models for accurate future prediction. Lower OEE outcome of combined factors is an indication that the company is operating below expectation. Process improvement is needed to correct the shortfall, and to survive in a competitive environment.

The results of improvement using six sigma metrics are presented in Table 6 including improvement results from other methods. The maximum continuous improvement level of OEE' (0.77) is attainable over the initial minimum OEE (0.81). The outcomes revealed that about 77% improvements are achievable by the application of smart OEE-sigma model across all performance factors over the base values. Under the traditional dynamic method, the firm is operating within (at least) OEE of 0.81. Smart OEE-six sigma approach yielded improvement increase of 0.77 over the base value (0.81) and hence, eradicated shortfall in the production process. Attainment of more 0.77 improvement from the new smart OEE-sigma technique is a significant success over previous schemes-lean bundle and lean green models, in which improvement variations of 0.23 [13], and 0.20 [24] were obtained, respectively.

| OEE Factor (y) | Prediction model (at year x) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Availability Expected ($R^2$=0.9912) | $y = 2.4673x^6 - 63.552x^5 + 587.96x^4 - 2231.9x^3 + 2195.6x^2 + 5815.7x + 3668.3$ | 9,974.58 | 13,758.50 | 14,594.79 | 14,765.67 | 16,075.86 | 18,443.86 | 20,269.77 | 20,579.62 |
| Availability Delivered ($R^2$=0.9992) | $y= -2.7512x^6 + 82.94x^5 - 975.96x^4 + 5655.7x^3 - 16801x^2 + 25373x - 2119.2$ | 11,212.73 | 13,531.04 | 14,590.74 | 16,337.48 | 17,908.30 | 18,651.29 | 19,164.59 | 20,354.39 |
| Quality-Expected ($R^2$=0.9942) | $y = 0.0031x^6 - 0.0823x^5 + 0.8438x^4 - 4.2353x^3 + 10.682x^2 - 11.654x + 79.437$ | 74.99 | 76.04 | 76.87 | 77.11 | 77.43 | 77.47 | 76.03 | 73.42 |
| Quality-Delivered ($R^2$=0.9796) | $y = 0.0276x^6 - 0.7996x^5 + 9.2103x^4 - 53.372x^3 + 161.19x^2 - 231.88x + 192.6$ | 76.98 | 70.17 | 78.48 | 80.41 | 80.39 | 82.37 | 83.32 | 86.53 |
| PerformanceExpected ($R^2$=0.9845) | $y = -0.000x^6 + 0.018x^5 - 0.197x^4 + 1.109x^3 - 3.491x^2 + 6.182x + 86.37$ | 89.99 | 91.07 | 91.86 | 94.22 | 101.76 | 121.99 | 168.50 | 263.12 |
| PerformanceDelivered ($R^2$=0.9865) | $y = -0.052x^6 + 1.467x^5 - 16.28x^4 + 89.92x^3 - 255.3x^2 + 339.9x - 69.62$ | 90.04 | 91.48 | 80.11 | 81.596 | 84.26 | 84.1 | 92.38 | 105.71 |

Table 4. Overall Equipment Effectiveness  Parameters Prediction Results

| x | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| f(α) | 1.0 | 1.00 | 0.97 | 1.00 | 1.00 | 0.97 | 0.98 | 0.98 |
| f(μ) | 1.0 | 0.92 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| f(β) | 1.0 | 1.00 | 0.87 | 0.86 | 0.89 | 0.84 | 0.86 | 0.89 |
| OEE | 1.0 | 0.92 | 0.84 | 0.86 | 0.89 | 0.81 | 0.84 | 0.87 |
| x, years, f(α), availability, f(μ), quality, f(β), performance, OEE, overall equipment effectivenss | | | | | | | | |

Table 5. Individual and Combined OEE Prediction

| OEE metrics per year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Traditional based dynamic OEE | 1.00 | 0.92 | 0.84 | 0.86 | 0.89 | 0.81 | 0.84 | 0.87 |
| Smart OEE-sigma (OEE') improvement over tradition | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 |
| Lean bundle (Shah and Ward, 2003) | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Lean green (Pampanelli et al., 2014) | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| Manufacturing Execution System-MES (Hedman et al., 2016) | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 |

Table 6. Continuous improvement on OEE using six-sigma metric and other methods

On the individual OEE factors, 0.99, 0.76 and 0.72 for the quality, availability and performance were reported respectively [15]. The productivity performance results ranging from 0.97-1.0, 0.92- 1.0, and 0.86-1.0 were achieved respectively for the availability, quality, and performance for the years under review (Table 8). This showed that the company had not performed badly as compared with similar performances in the past [15]. The three-factored OEE performance achieved in the company using smart model was in the range 0.81 - 1.0. This outcome is superior to average OEE of 0.65 computed from Manufacturing Execution Systems (MES) [4]. The findings showed that the smart OEE-sigma metric technique proposed is more sustainable than other improvement schemes identified in literature (Table 6).

## 8. CONCLUSION

The study has identified and integrated the OEE parameters from which a new smart OEE-sigma model was formulated as a tool to enable continuous improvement in an ailing production process. The tool was able to consider all aspects of production processes covering operations, the equipment in use, and customers' satisfaction with the aim of eliminating all barriers that could hinder optimal performance. The tool was applied to capture and improve system availability, system performance, and system quality of the fast moving good production company in line of satisfying customers' demand, without inventory challenge. Utilisation of six-sigma metric as a continuous improvement tool in the new OEE scheme has recorded a landmark achievement by attaining the highest level of overall equipment effectiveness improvement as compared with other tools utilized in the past. The landmark achievement from the use of six-sigma metric as a continuous improvement tool can be attributed to its excellent accuracy in measuring statistical process variations.

The findings showed that the manufacturing industry under consideration required improvement scheme in its operations as regards OEE virtually in all parameters under consideration. The deficiency in the traditional OEE model was revealed by the outcomes obtained after integration of sigma improvement factor. The new OEE metric enabled effectiveness in man-hour utilisation by disallowing laziness at work in which the Single Minute Exchange of Die (SMED) strategy played important role. This is demonstrated by improvement in OEE of the plant by 77% of its previous value. It can be concluded from the outcomes that the developed OEE' metric is a better tool for monitoring, controlling and evaluating overall equipment effectiveness in a dynamic production environment. Effective management of production output with size of customer's demand, effective analysis of root cause of ineffectiveness in production system and process continuous improvement strategy can be achieved using sigma metric process variation tool. Areas of production environment including ergonomics, waste generation and production floor integrity should be looked at in the future endeavour. Inclusion of these factors would lead to hypothesis testing. Null hypothesis will be- inclusion of the stated factors will have significant effect on the OEE of the company, while the alternative hypothesis would be there is no significant difference between them. Under this management, it is believed that efficacy of integrating sigma metric into OEE model as improvement tool will be clearer.

## 9. REFERENCES

[1] Bruce, C. H: *Best Practices in Maintenance,* http://www.tpmonline.com/articles_ on_total_productive_maintenance/management.htm, accessed 26:09:2011.

[2] Aminuddin, N. A. B.: *An analysis of managerial factors affecting the implementation and use of overall equipment effectiveness*, Warwick Manufacturing Centre, The University of Warwick Coventry, United Kingdom, 2015.

[3] Nakajima, S. (2000): *Introduction to Total Productive Maintenance,* Productivity Press,

Cambridge M. A., London, 2000

[4] Hedman, R., Subramaniyan, M., Almström, P.: *Analysis of Critical Factors for Automatic Measurement of OEE,* Procedia CIRP, 57, 128-133, 2016.

[5] AFSC-Air Force Systems Command.: *Human Factors Engineering,* Air Force Systems Command Design Handbook (3rd ed.). United Kingdom, 2010.

[6] Alexander, D. C.: *The Practice and Management of Industrial Ergonomics.* Englewood Cliffs, NJ: Prentice-Hall. USA, 2012.

[7] Adams, J. A.: Human Factors Engineering. New York: McMillan Publishing, 2014.

[8] Michael, J.K.: *Six Sigma Green Belt Training manual,* Michael JK (UK Based), 2015.

[9] Künsch, H.R., Stefanski, L.A., Carroll, R.J.: *Conditionally Unbiased Bounded-Influence Estimation in General Regression Models, with Applications to Generalized Linear Models,* Journal of the American Statistical Association, 84 (406) 23-37, 2012.

[10] Swamidassa, P.M., Kothab, S.: *Explaining manufacturing technology use, firm size and performance using a multidimensional view of technology,* Journal of Operations Management, 17(1) 23-37, 1998.

[11] Ljungberg, O.: *Measurement of overall equipment effectiveness as a basis for TPM activities,* International Journal of Operations & Production Management, 18(5) 495-507, 1998.

[12] Hansen, R.C.: Overall equipment effectiveness: a powerful production/ maintenance tool for increased profits, 275pp., Industrial Press Inc. New York, 2002.

[13] Shah, R., Ward, P.T.: *Lean manufacturing: context, practice bundles, and performance*, Journal of Operations Management, 21(2) 129-149, (2003).

[14] Braglia, M., Frosolini, M., Zammori, F.: Overall equipment effectiveness of a manufacturing line (OEEML): *An integrated approach to assess systems performance,* Journal of Manufacturing Technology Management, 20(1) 8-29, 2008.

[15] Wilson, L.: How to Implement Lean Manufacturing, 335pp, The McGraw-Hill Companies, Inc. New York,. 2010.

[16] Almeanazel, O.T.R.: *Total Productive Maintenance Review and Overall Equipment Effectiveness Measurement,* Jordan Journal of Mechanical and Industrial Engineering (JJMIE), 4(4) 517 – 522, 2010.

[17] Garza-Reyes, J. A., Eldridge, S., Barber, K. D., Soriano-Meier, H.: *Overall equipment effectiveness (OEE) and process capability (PC) measures: A relationship analysis,* International Journal of Quality & Reliability Management, 27(1): 48-62, 2010.

[18] Madhavan, E., Paul, R., Rajmohan, M.: Study on The Influence of Human Factors, Euro Journals, 23, 179-192, 2011.

[19] Zuashkiani, A., Rahmandad, H., Jardine, A. K. S.: *Mapping the dynamics of overall equipment effectiveness to enhance asset management practices*, Journal of Quality in Maintenance Engineering, 17(1) 74-92, 2011.

[20] Dilworth, J.B.: *Production and Operations Management*, McGraw-Hill, New York, USA, 2013.

[21] Peng, L., Huang, Y.: *Survival Analysis with Quantile Regression Models,* Journal of the American Statistical Association, 103 (482) 637-649, 2012.

[22] Hayes, A.F.: *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-based Approach*, 692pp., 3rd edition, The Guilford Press, New York, , 2018.

[23] Marselli, M.: Lean manufacturing and six-sigma, Wire Journal International, http://www.aemconsulting.com/pdf/lean.pdf, accessed, 11: 04: 2018.

[24] Pampanelli, A.B., Found, P., Bernardes A.M.: *A Lean & Green Model for a production cell*, Journal of Cleaner Production, 85, 19-30, 2014.

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