Measuring Operational Excellence: An Operational Excellence Profitability (OEP) Approach

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Abstract

The pursuit of operational excellence in the manufacturing industry is at rise, but its measurement still lacks of appropriate indicators to determine its financial benefits. The ambiguity is due to the impact arisen from manufacturing fluctuations such as price and cost, production mix, and direct and indirect parameters variations. Manufacturing fluctuations distort the cost benefit of operational excellence. This paper therefore proposes the OEP (Operational Excellence Profitability) indicators to isolate the impact of manufacturing fluctuation, and distinctly identify the payback of operational excellence strategies and initiatives through cost benefits of achieving higher efficiency and yield. The paper presents the conceptual and mathematical development of the proposed OEP indicators and the formulas used for their calculation. Hypothetical and industrial-based investigations and applications of the OEP indicators are conducted for their validation. The results obtained from the hypothetical exercise and industrial case suggest that OEP indicators can provide an effective cost benefit analysis of operational excellence. This would contribute in providing manufacturing organisations with more complete information regarding the performance of their processes, which will allow their directors and managers to take better decisions related to the management and improvement of their processes.

Keywords: Operational excellence; performance; measurement; indicators; OEE.

1. Introduction

Fierce global competition and scarcity of resources have led to higher resource costs, and alongside customers' demand for lower sale prices (Andersson and Bellgran 2015), these have directly and negatively impacted the profitability of manufacturing companies, requiring them to achieve excellence in their operations (Olhager and Persson, 2006) as an strategy to counteract such current challenges (Wudhikarn 2016). In this line, the achievement of operational excellence is enabled by an appropriate measurement of operational performance, from which directors and managers can draw information to effectively and efficiently manage the operations and processes of their organisations (Garza-Reyes et al. 2010). The today's dynamic and competitive nature of the manufacturing environment requires decisions to be taken based on reliable metrics that assess performance rather than experiences and feelings (Tan and Noble 2007).

Various methods and techniques have been developed to measure and achieve operational excellence, but they often lack the explicit understanding and directions for decision-making (Grünberg 2004). The demand/push for operational excellence requires microscopic analyses of every aspect to identify the factors that contribute to the performance of operations (Grünberg 2004), in order to optimise such operations to extract and create maximum value for customers. In this scenario, multiple factors are considered, but yet they often fail to contribute in improving performance as most assessment measures and metrics of operational excellence focus on reducing input rather than on increasing outputs (Baines 1997). Grünberg (2004) highlights the fact that a company's profits might be increasing while having a stagnated productivity level. One of the most common and highly used metrics of operational excellence in the manufacturing industry is Overall Equipment Effectiveness (OEE) (Garza-Reyes 2015; Andersson and Bellgran 2015; Wudhikarn 2016).

OEE emerged as a result of Nakajima's Total Productive Maintenance (TPM) work, as an initiative to evaluate the progress achieved after the adoption of such improvement strategy (Nakajima 1988). OEE measures the performance of production equipment (Wudhikarn 2016), and serves as an indicator and driver of process and performance improvement (Garza-Reyes et al. 2010). OEE has been highly utilised in the manufacturing sector, and since its conception by the end of the 1980s it has been the subject of constant research and further development by scholars (Aminuddin et al. 2016). In general, OEE evaluates the effectiveness of machines performance and identifies production losses based on their availability (i.e. operating time), performance (i.e. speed) and quality (i.e. number of defects) (Muchiri and Pintelon 2008).

However, despite OEE's wide popularity, scholars have acknowledged and debated whether a single measure and/or the measurement of individual production equipment are enough to effectively assess operational excellence (Hermel and Ramis-Pujol 2003). For this reason, despite OEE's prominent contribution to the continuous improvement field, its limitations have prompted a prominent stream of research to expand its scope and/or modify the way in which it is calculated so it can serve its purpose (Wudhikarn 2016) of contributing towards operational excellence, see Table 1.

Table 1. OEE's research stream – scope expansion and calculation modifications

Developments / Modification	***Scope Extension***	***Calculation Modification***	***By***
Different weights for different elements		☑	(Raouf 1994)
OPE (overall process effectiveness)	☑		(Al-Najjar 1997)
OFE (overall factory effectiveness)	☑		(Scott and Pisa 1998)
OFE (overall fab effectiveness)	☑		(Oechsner et al. 2002)
Production losses quantified in monetary units		☑	(Kwon and Lee 2004)
OLE (overall line effectiveness)	☑		(Nachiappan and Anantharaman 2006)
(E) measure: stand-alone equipment effectiveness		☑	(Ron and Rooda 2006)
OTE (overall throughput effectiveness)	☑		(Muthiah and Huang 2007)
OEEML (overall equipment effectiveness of the manufacturing line)	☑		(Braglia et al. 2008)
ORE (overall resource effectiveness)		☑	(Garza-Reyes et al. 2008; Garza-Reyes 2015)
OECL (overall equipment cost loss)		☑	(Wudhikarn et al. 2010; Wudhikarn 2016)
OLE a performance evaluation index	☑		(Raja et al. 2010)
SOEE (Stochastic overall equipment effectiveness)		☑	(Zammori et al. 2011)
FOEE (fuzzy overall equipment effectiveness)		☑	(Zammori 2015)
OEM (overall material usage effectiveness)		☑	(Braglia et al. 2018)

In line with the research on OEE presented in Table 1, Raouf (1994) suggested as a limiting characteristic of OEE the fact that it assigns similar weights to its elements while the factors affecting performance are not similar. Consequently, he proposed a calculation modification by assigning different weights to different elements (Raouf 1994). Al-Najjar (1997) extended the scope of OEE by proposing OPE (overall process effectiveness) to measure all losses associated to entire processes, rather than simply those associated to individual equipment. In the same scope, Scott and Pisa (1998) proposed OFE (overall factory effectiveness) to measure the effectiveness of processes involving multiple machines/operations. Oechsner et al. (2003) developed OFE (overall fab effectiveness), a broader approach that incorporates the operation of individual production equipment in relation to other operating equipment. Kwon and Lee (2004) modified OEE's calculation by quantifying production losses in monetary terms. This contributed in determining a decreasing costs from an increasing percentage of OEE. Nachiappan and Anantharaman (2006) proposed OLE (overall line effectiveness) to measure the performance of a continuous line manufacturing system, under the realisation that OEE was only limited to measure the effectiveness of individual machines but not entire manufacturing lines with multiple machines in series. Ron and Rooda (2006) proposed (E) equipment effectiveness, to measure the effectiveness of stand-alone equipment isolated from the environment and on the basis of available effective time rather than total time. Muthiah and Huang (2007) proposed OTE (overall throughput effectiveness) to measure performance at entire factory level, as OEE lacked that characteristic. Garza-Reyes et al. (2008) and Garza-Reyes (2015) developed ORE (overall resource effectiveness) in realisation that that OEE does not measure the effective utilisation of materials and other resources. ORE modified the original OEE metric by integrating material efficiency, material cost, and process cost to measure overall effectiveness. Braglia et al. (2008) proposed OEEML (overall equipment effectiveness of the manufacturing line) as an integrated approach to measure the performance of an entire production system as opposed to individual equipment. This metric identifies where major inefficiencies take place and anticipates the advantage of corrective actions. Wudhikarn (2009; 2016) proposed OECL (overall equipment cost loss) to evaluate the performance of different pieces of equipment by ranking multiple problematic machines in terms of cost losses. Raja et al. (2010) introduced the OLE (overall line effectiveness) index in realisation that traditional metrics only measure part of the performance of manufacturing equipment but do not contribute in identifying the actual problem. OLE evaluates the performance of a production line by assessing the quality rate using PCA (principal component analysis). Zammori et al. (2011) proposed SOEE (stochastic overall equipment effectiveness) as OEE only provides a static representation of a process but not the actual variability of manufacturing performance. Zammori (2015) developed FOEE (fuzzy overall equipment effectiveness) to observe the day-to-day fluctuations in manufacturing performance, by digging the root causes of manufacturing losses and modelling them as LR fuzzy numbers. The purpose of FOEE was to ensure the accuracy and robustness of results. Finally, Braglia et al. (2018) proposed OME (overall material usage effectiveness) to not only comprehend material related issues but also identify viable countermeasures.

The aforementioned modifications made to OEE have expanded its scope to also consider other performance dimensions which may be important to ponder/assess when measuring the performance of operations. However, there yet is another challenge to measure the exact cost benefit of operational excellence in manufacturing operations. The ambiguity is due to the impact arisen from fluctuations in manufacturing processes. Manufacturing fluctuations are indirect elements that distort the cost benefit of operational excellence, see Section 2. Therefore, the aim of this paper is to propose a novel set of indicators, called Operational Excellence Profitability (OEP), which isolates the impact generated by the aforementioned fluctuations in manufacturing environments so that the cost benefits achieved through operational excellence in manufacturing operations are determined.

2. Fluctuations in Manufacturing Processes

Manufacturing cost per unit, a key performance measure (Andersson and Bellgran 2015), is the sum of costs of all resources consumed in the process of making a product compared to the production output. Manufacturing cost is comprised of direct materials (e.g. raw materials and the packaging materials cost, etc.) (S. Huang and Yang 2016), direct labour (e.g. dedicated shop-floor personnel, etc.) (Wacker, Yang, and Sheu 2006), direct consumables (e.g. lubricants, water if not used as a raw material, etc.) and indirect consumables (e.g. electricity, bunker, gas, etc.) (Wu and Chen 2017), spare parts (Qiwei et al. 2018) and other manufacturing overhead costs, see Figure 1.

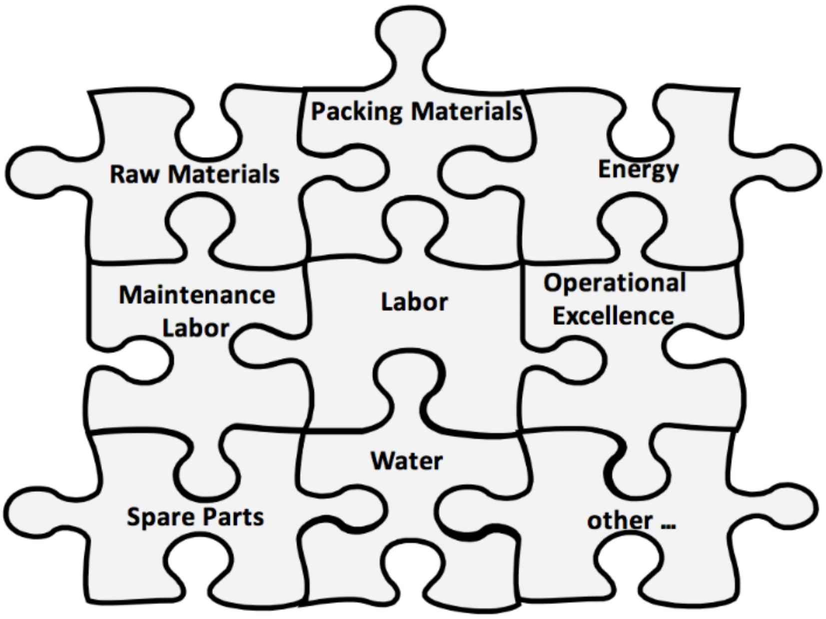

Figure 1. Elements that impact manufacturing costs

Another key metric besides manufacturing cost is productivity, a ratio between what is produced and what is required to be produced (Andersson and Bellgran 2015; Kaplan and Cooper 1998). What is produced refers to the goods and services manufactured, whereas what is required to be produced are resources (Andersson and Bellgran 2011) representing manufacturing costs. Productivity is also defined as the value added compared to the input of manufacturing resources (Aspen et al. 1991; Tomiura 2007; Brandt, Van Biesebroeck, and Zhang 2012). Others define productivity as an outcome/result of efficiency and effectiveness (Hill 2000; Roghanian, Rasli, and Gheysari 2012), where efficiency is considered as the ratio of the actual output and the expected number, and effectiveness is the ratio of expected resource consumption and the actual resource consumption.

The cost of manufacturing per unit and productivity metrics vary due to manufacturing fluctuations and a factory's operational performance; operational performance as related to reducing time and yield losses. Manufacturing fluctuations are typically present through labour costs per man hour, raw and packaging materials prices, production mix, production demand, and parameters of direct and indirect costs. In particular, manufacturing fluctuations may include:

Price and cost variances

Prices of raw and packaging materials can change (Grünberg 2004; Liu and Yang 2015) at any moment due to different circumstances such as change of price from the current supplier, use of other vendors' materials, market price increase for a specific component, etc. Labour costs can also shift (Garza-Reyes 2015; S. Huang and Yang 2016) due to changes in current employee salaries, new labour compensations, new salaries for new employees, new employee retention strategies, and alike.

Production mix variation

Production mix refers to the amount of different finished products manufactured per interval of time (Fernandes, Gouveia, and Pinho 2012). An industry can manufacture different production mix per month; for example, 10 units of finished product A and 20 units for finished product B for the first month, and for the following month 25 of A and 10 of B. Production mix has a significant impact on manufacturing cost per unit, since the raw material composition of each product might be different, as well as other resources required (e.g. packaging materials, direct labour cost, and direct and indirect consumables cost, etc.), which in-turn can have a direct impact on total manufacturing cost per unit.

Direct and indirect cost parameters variances

Changes in parameters of direct and indirect costs can also have a considerable effect in manufacturing costs; for example, the cost of electricity per KWh, the cost of maintenance technicians labour extra hours, the cost of bunker per Kg, etc.

Operational excellence

Operational excellence also has a considerable impact on manufacturing cost (Andersson and Bellgran 2015). As the factory's operational excellence determines process efficiency and yield, the manufacturing cost is affected by process losses in time and in packaging and raw materials. A factory with a higher operational excellence exhibits a better process yield and efficiency (Jaeger, Matyas, and Sihn 2014), or better OEE. When there is an increase in intermediate or finished product loss, the factory requires more time and packaging and/or raw materials, for the manufacturing of the same number of finished products.

The cost of manufacturing per unit and the productivity metric commonly varies every week or month due to manufacturing fluctuations and operational excellence. It is not possible for the manufacturing facility to isolate the cost benefit of increasing operational excellence from the variations of the manufacturing-fluctuations elements. Thus, there is a need to develop indicators to isolate the impact of manufacturing fluctuations in order to clearly understand the cost benefits of achieving a better operational excellence level.

3. Operational Excellence Profitability (OEP) Indicators Proposed

Andersson and Bellgran (2015) acknowledge that using OEE itself is not sufficient to capture cost benefits, and hence proposed two additional indicators: Part Pace and Cost per Part Produced. However, despite both indicators are sensitive to manufacturing fluctuations, they do not isolate the impact of operational excellence. Sheu (2006) introduced a new indicator to account for the efficiency of input resources use.

Nonetheless, this metric is not designed to isolate operational excellence efforts or to uniquely identify them. Grünberg (2004) reasons that using productivity indicators with monetary units has the problem that they need to be deflated (adjusting for inflation); hence, these are not considered suitable to monitor operational performance. Nonetheless, if monetary units are not incorporated, then manufacturers will not be able to determine cost benefits and appoint the profitability of improvement initiatives.

Manufacturing fluctuations distort the cost benefit of operational excellence. Thus, a gap exists in manufacturing indicators to identify the payback of operational excellence so manufacturers could clearly identify which plant floor initiatives are most beneficial.

The proposed OEP indicators are a set of metrics designed to assess the cost benefit of improving operational excellence by isolating the impact of manufacturing fluctuations. OEP indicators distinctly establish the payback of operational excellence from the point of view of each component of the manufacturing cost, by proposing an indicator for each component of the manufacturing cost.

The OEP indicators are not an extension of the OEE metric. OEE is a measure of efficiency and yield for a process (Garza-Reyes 2015); instead, the OEP indicators can be best described as a set of metrics that measure the cost benefit of improving operational excellence by isolating the impact of fluctuations in manufacturing processes.

The proposed set of OEP indicators consist of:

- OEP Energy Consumption, $\mathrm{OEP(ECp)}$;
- OEP Direct Labour Used, $\mathrm{OEP(DLU)}$;
- OEP Raw Material Loss Indicator, $\mathrm{OEP(RML)}$;
- OEP Packaging Material Loss Indicator, $\mathrm{OEP(PML)}$;
- OEP Maintenance Labour Extra Time Indicator, $\mathrm{OEP(MLE)}$;
- OEP Maintenance Spare Parts Indicator, $\mathrm{OEP(SPC)}$.

To show the economic improvement in operational excellence, the OEP indicators set for an evaluating period is compared to the OEP results for a base period. The periods could be any time interval such as weeks, months or years. The following sections present the development of the OEP indicators.

3.1 OEP Energy Consumption indicator, $\boldsymbol{OEP(ECp)}$

Energy is an indirect consumable of the manufacturing cost (i.e. electricity, bunker, gas) (Xu et al. 2012), and is considerably sensitive to manufacturing fluctuations. The energy bill varies in line with the energy consumption and the price per energy unit; at the same time, energy consumption depends on the production mix, production demand and operational excellence.

Production lines exhibit an energy consumption that has two components: fixed energy consumption and variable energy consumption. The fixed component represents a constant energy consumption regardless of the speed of production, whereas the variable component is proportional to the speed of production. In practice, the fixed component is significantly higher than the variable component. Hence, finished products that have higher production speeds tend to consume slightly higher energy than those that have slower production speeds.

In this line of thought, a production mix that has finished products with high production speeds will tend to show just a slight increase in energy consumption than a production mix with low-speed finished products during a specific time interval. Energy consumption per production unit will tend to decrease with high-speed production mix since the slight increase in energy consumption is usually offset by the increase in production units.

Energy consumption is proportional to production demand. As the facility needs to produce more units, requiring more time for operations and therefore energy consumption. Energy consumption is also inversely proportional to operational excellence. As operational excellence decreases, the facility exhibits higher time and/or yield losses; requiring more time for demand production and therefore more energy consumption.

The OEP Energy Consumption indicator isolates the cost benefit impact due to operational excellence from manufacturing fluctuations. This indicator establishes the relationship between energy consumption and production output, compensating the production mix effect.

The OEP Energy Consumption indicator compensates the manufacturing fluctuation production mix by using the concept of the effective theoretical speed of production, the time average of the theoretical speeds for the finished products that were manufactured in a specific production line. The **effective theoretical speed of production** line j for year y, TSd_j^y, is defined as:

$$\boldsymbol{TSd_j^y} = \sum_{i=1}^{Finished\ Products} \frac{TSd_{i,j}^y MTm_{i,j}^y}{MTm_j^y} \qquad (1)$$

In production units divided by time units; production units can be expressed in counting, volume (such as hectolitres) or weight (such as kilograms) units.

Where:

$MTm_{i,j}^y$ is the Manned Time for Finished Product i, in production line j.

MTm_j^y is the total Manned Time for production line j.

$(TSd_{i,j}^y)$ is the Theoretical Speed for Finished Product i, in line j, during year y.

Manned time is defined as the sum of periods where direct labour is present in the production line j. $\mathrm{TSd}_{\mathrm{i,j}}^{\mathrm{y}}$ is the technical line bottleneck maximum speed for Finished Product i, expressed in production units per time unit. The MTm_j^y is the total manned time for production line j, and it is defined as:

$$MTm_j^y = \sum_{i=1}^{\#\ Finished\ Products} MTm_{i,j}^y \qquad (2)$$

The averaging of the effective theoretical speed of production is based on time and not on production units, since most energy cost savings are based on time, as well as the fact that manufacturing facilities usually pay energy bills based on time.

The **OEP Energy Consumption indicator**, $OEP(ECp_j^y)$, represents the relationship between the energy consumption of a production line in relation to its output, compensating the production mix effect. It is defined as:

$$\boldsymbol{OEP(ECp_j^y)} = \frac{ECp_j^y}{\frac{TSd_j^{base}}{TSd_j^y} Prd_j^y} \qquad (3)$$

In energy units (such as KWh) divided by production units; production units can be expressed in counting, volume (such as hectolitres) or weight (such as kilograms) units.

Where:

ECp_j^y is the energy consumption, in energy units, for production line j in the year y.

Prd_j^y is the output production, in production units, for production line j, during year y.

TSd_j^{base} is the theoretical speed for production line j, during the $base$ year.

TSd_j^y is the theoretical speed for production line j, during year y.

By incorporating the factor $\frac{TSd_j^{base}}{TSd_j^y}$, the OEP Energy Consumption indicator is compared in a better way to the base year. If TSd_j^{base} is lower than TSd_j^y, then the factor $\frac{TSd_j^{base}}{TSd_j^y}$ will decrease the output production for year y. If TSd_j^{base} is higher than TSd_j^y, then the factor $\frac{TSd_j^{base}}{TSd_j^y}$ will increase the output production for year y. Thus, the effect of the production mix is compensated.

As a good practice, the output production value, Prd_j^y, must be taken from the units that are recorded as entering the finished product warehouse. It is desirable that energy consumption, ECp_j^y, be measured directly by an automated device. If not, technical factors need to be determined in order to prorate the energy bill.

The **energy saving benefit**, SBE_j^y, is determined by the equation:

$$\boldsymbol{SBE_j^y} = \left[OEP\left(ECp_j^{base}\right) - OEP\left(ECp_j^y\right)\right] \times Prd_j^y \times ECE_j^y \qquad (4)$$

Where:

$OEP\left(ECp_j^{base}\right)$ is the OEP Energy Consumption Indicator for production line j and during the $base$ year.

$OEP\left(ECp_j^Y\right)$ is the OEP Energy Consumption Indicator for production line j and during year y.

ECE_j^y is the Energy Cost per Energy unit for production line j during year y.

SBE_j^y Saving Benefit in Energy for production line j and during year y.

If the Energy Saving Benefit calculation results in a negative number, then the benefit represents a loss compared to the base year. By subtracting the OEP Energy Consumption Indicators first, and then multiplying it by the unitary energy cost and output production, the energy cost manufacturing fluctuation is mitigated. As a good practice, the energy cost must include the monetary amount of the energy consumption bill, as well as any other cost that the utility company may charge.

Improvements in the consumption of electricity, diesel, oil, gas, steam, water, and other industrial consumables, can be determined through the use of the OEP Energy Consumption indicator.

3.2 OEP Direct Labour Used indicator, $OEP(DLU)$

Direct labour refers to the dedicated shop-floor personnel and is sensitive to manufacturing fluctuations (Leung et al. 2007) as it depends on the direct labour costs per man-hour, number of man-hours of direct personnel in the shop-floor. Similarly, the number of man-hours depends on the production mix, production demand and operational excellence.

Some production processes require standard staff of direct personnel, while others need a reduced or more staff based upon the production mix. Production mixes with enlarged staff will force the factory to exhibit a higher direct labour cost, while production mixes with reduced staff will have lower direct labour costs. Thus, the sensitivity of the direct labour cost to the production mix.

Direct labour man-hours is proportional to production demand, higher production output will require more time and therefore man-hours. Direct labour is also inversely proportional to operational excellence. As operational excellence decreases, the facility exhibits higher time and/or yield losses; it will take more time to produce the required demand and therefore will require more man-hours.

The OEP Direct Labour Used indicator isolates the cost benefit impact due to operational excellence from the manufacturing fluctuations by establishing the relationship between the direct labour used and output production, weighting the production mix effect.

The OEP Direct Labour Used indicator compensates the manufacturing fluctuation production mix by using the concept of the effective theoretical staff of production, which is the time average of the theoretical staff for the finished manufactured products in a specific production line. The **effective theoretical staff of production** line j for year y is defined as:

$$TSf_j^y = \sum_{i=1}^{\#\,Finished\ Products} \frac{TSf_{i,j}^y MTm_{i,j}^y}{MTm_j^y} \qquad (5)$$

In number of persons.

Where:

$MTm_{i,j}^y$ is the Manned Time for Finished Product i, in line j.

MTm_j^y is the total Manned Time for line j.

$TSf_{i,j}^y$ is the theoretical staff for finished product i, in line j, expressed in number of persons.

The $TSf_{i,j}^y$ is the number of persons that are required to manufacture product i, in production line j as established in the factory.

The OEP Direct Labour Used indicator, $OEP(DLU_j^y)$, establishes the relationship between the direct labour used in line j in relation to its output production. It is defined as:

$$OEP(DLU_j^y) = \frac{\frac{TSf_j^{base}}{TSf_j^y} DLU_j^y}{\frac{TSd_j^{base}}{TSd_j^y} Prd_j^y} \qquad (6)$$

In man-hours divided by production units; production units can be expressed in counting, volume (such as hectolitres) or weight (such as kilograms) units.

Where:

DLU_j^y is the Direct Labor Used for line j in the year y, expressed in man-hours.

Prd_j^y is the output production, in production units, for production line j, during year y.

TSf_j^{base} is the theoretical staff for production line j, during $base$ year.

TSf_j^y is the theoretical staff for production line j, during year y.

TSd_j^{base} is the theoretical speed for production line j, during the $base$ year.

TSd_j^y is the theoretical speed for production line j, during year y.

By incorporating the factor $\frac{TSf_j^{base}}{TSf_j^y}$, the OEP Direct Labor Used indicator, $OEP(DLU_j^y)$, is compared in a better way to the base year. If TSf_j^{base} is lower than TSf_j^{base} then the factor $\frac{TSf_j^{base}}{TSf_j^y}$will decrease the direct man-hours for year y. If TSf_j^{base} is higher than TSf_j^{base}, then the factor $\frac{TSf_j^{base}}{TSf_j^y}$ will increase the direct man-hours for year y. Thus, the effect of the production mix is compensated in the numerator of the $OEP(DLU_j^y)$ expression. The factor $\frac{TSd_j^{base}}{TSd_j^y}$ compensates the output production for year y as explained in Section 3.1. The effects of staff variations and the effects of production mix are mitigated.

As a good practice, it is recommended to record, directly, the number of persons at any given time in the production line j, and avoid using the data in the payroll or attendance system. This is because, at any time, the direct line personnel can be assigned different tasks in the plant floor that do not relate to the line j activities.

The **OEP Direct Labour Saving Benefit**, SBL_j^y, is determined by:

$$\boldsymbol{SBL_j^y} = \left[OEP(DLU_j^{base}) - OEP(DLU_j^y)\right] \times Prd_j^y \times LCH_j^y \qquad (7)$$

Where:

$OEP(DLU_j^{base})$ is the OEP Direct Labour Used Indicator for production line j and during the $base$ year.

$OEP\left(DLU_j^y\right)$ is the OEP Direct Labour Used Indicator for production line j and during year y.

LCH_j^y is the Labour Cost per man-hour for production line j during year y.

SBL_j^y Saving Benefit in Labour for production line j and during year y.

If the OEP Direct Labour Saving Benefit calculation results in a negative number, then the benefit represents a loss compared to the base year.

The labour cost manufacturing fluctuation is mitigated by subtracting the OEP Direct Labour Used Indicators first, and then multiplying it by the labour cost per man-hour and output production.

As a good practice, the Labour Cost per man-hour, LCH_j^y, must include salaries, social costs and all employee benefits.

3.3 OEP Raw Material Loss indicator, $\boldsymbol{OEP(RML)}$

Raw material, unprocessed materials used in the manufacturing or production of finished products, is part of the direct materials component of the manufacturing cost. The raw materials loss cost represents the raw materials waste cost during the production process as well as the overfill/over usage in certain specific processes (Garza-Reyes 2015).

Raw material losses vary with operational excellence and manufacturing fluctuations such as vendor's price (Liu and Yang 2015), production mix and production demand. As the price of the raw material increases, the loss cost also increases. A production mix, an important manufacturing fluctuation, with more expensive raw materials will show higher cost losses; while a production mix with less expensive raw materials will show lower cost losses; thus, raw material loss cost shows sensitivity to the production mix. Even further, the production mix, which has products with higher processability in the production line, will show lower cost losses; while production mix that has products with lower processability, will show higher cost losses. Raw material price and processability per finished product presents a combination that makes the production mix effect almost unpredictable with respect to the cost loss. For example, there could be a production mix with more expensive raw materials, but with high processability products, that could tend to decrease the raw materials cost loss regardless of its pricing.

Raw material loss is also proportional to production demand. As the facility needs to produce more units then it will require more raw materials; therefore, there will be more raw material losses. Raw material loss is also inversely proportional to operational excellence. As operational excellence decreases, the facility might exhibit higher yield losses; it will take more raw materials to produce the required production demand.

The OEP Raw Material Loss indicator isolates the cost benefit impact due to operational excellence from the manufacturing fluctuations. It establishes the relationship between raw material losses, during a manufacturing process, and the production output.

The OEP Raw Material Loss Indicator, $OEP(RML_j^y)$, establishes the relationship between the raw materials loss in line j in relation to its output production. Sometimes, it is not possible to technically determine the quantity of raw materials that are supplied directly to a specific line. In these cases, the indicator must be calculated for the entire shop-floor. The indicator is defined as:

$$\boldsymbol{OEP}(\boldsymbol{RML}_{\boldsymbol{j}}^{\boldsymbol{y}}) = \frac{\Lambda RM_j^y}{Prd_j^y} \qquad (8)$$

In production units divided by production units; production units can be expressed in counting, volume (such as hectolitres) or weight (such as kilograms) units.

Where:

ΛRM_j^y is the yield drop in raw materials for production line j and during year y.

Prd_j^y is the output production, in production units, for production line j, during year y.

The term $\frac{TSd_j^{base}}{TSd_j^y}$ does not show up since it is required in the numerator and denominator of the indicator.

As a good practice, the yield drop in raw materials, ΛRM_j^y, must be calculated directly through mass and weight instruments, or counters, on the plant floor. If these types of measurements are not available, then the raw material loss can be derived from the accounting systems. It is recommended in the Food & Beverage sector to always account for water weight and authorised overweight when comparing the actual weight going into the finished product warehouse with the incoming raw materials weight.

The **OEP Raw Materials Loss Saving Benefit**, SBR_j^y, is determined by the equation:

$$\boldsymbol{SBR}_{\boldsymbol{j}}^{\boldsymbol{y}} = \left[OEP\left(RML_j^{base}\right) - OEP(RML_j^y)\right] \times Prd_j^y \times RMC_j^y \qquad (9)$$

Where:

$OEP\left(RML_j^{base}\right)$ is the raw material loss for production line j, during $base$ year.

$OEP\left(RML_j^y\right)$ is the raw material loss for production line j, during year y.

RMC_j^y is the Raw Materials Average Cost per production unit for production line j and during year y.

If the OEP Raw Materials Loss Saving Benefit calculation results in a negative number, then the benefit represents a loss compared to the base year. By subtracting the OEP Raw Material Loss indicators first and then multiplying it by the raw materials average cost and output production, the raw material prices manufacturing fluctuation is mitigated.

3.4 OEP Packaging Material Loss indicator, $\boldsymbol{OEP}(\boldsymbol{PML})$

Packaging materials are part of the direct materials component of the manufacturing cost. Packaging materials take into account primary and secondary packaging materials that envelops the product and restrains it (Zhang and Zhao 2012). Secondary packaging materials are outside the primary packaging and are typically labels, security seals or any material that groups primary packages together, such as boxes. Packaging materials usually have an important percentage in the manufacturing cost (Roy et al. 2011).

Packaging materials loss cost represents the packaging materials waste cost during the production process. It varies with operational excellence and manufacturing fluctuations such as the vendor's price, the production mix and production demand. As the price of the packaging material increases, the loss cost increases as well. A production mix with expensive packaging material will show higher cost losses; while a production mix with less expensive packaging materials will show lower cost losses; thus, the packaging material loss cost presents sensitivity to the production mix. Even further, the production mix, that has products with higher processability in the production line, will show lower cost losses; while production mix that has products with lower processability, will show higher packaging materials cost losses. The packaging material price and processability per finished product presents a combination that makes the production mix effect almost unpredictable with respect to this cost loss. As an example, there could be a production mix with more expensive packaging materials, but with high processability products that could tend to decrease the packaging materials cost loss regardless of its pricing.

Packaging material loss is also proportional to production demand. As the facility needs to produce more units then it will require more packaging materials; therefore, there will be more packaging material losses. Packaging material loss is also inversely proportional to operational excellence. As operational excellence decreases, the facility might exhibit higher packaging yield losses; it will take more packaging materials for the required production demand.

The **OEP Packaging Materials Loss Indicator**, $OEP(PML_j^y)$, establishes the relationship between the packaging materials loss in line j with respect to its output production. The indicator is defined as:

$$\boldsymbol{OEP(PML_j^y)} = \frac{\Lambda PM_j^y}{\mathrm{InU}_j^y} \qquad (10)$$

In counting units divided by counting units.

Where:

ΛPM_j^y is the Loss Units for production line j during year y.

InU_j^y Incoming Units for production line j during year y.

The term $\frac{TSd_j^{base}}{TSd_j^y}$ does not show up since it is required in the numerator and denominator of the indicator.

There can be individual OEP Packaging Material Loss indicators for each type of packaging material such as jars, bottles, labels, caps, boxes, etc. For example, the Packaging Bottle yield for a filler line can be established as:

$$\Lambda_{bottles} PM_j^y = \sum_{p=1}^{production\ orders} \left[\mathrm{InU}_{p,j}^y - \mathrm{OtU}_{p,j}^y\right] \qquad (11)$$

Where all variables are expressed in number units and OtU_j^y is the output units for production line j during year y. In this case, $\mathrm{InU}_{p,j}^y$ is set equal to the bottles entering the production line j; the OEP Packaging Bottles Loss indicator is then:

$$OEP(PML_{bottles,j}^{y}) = \frac{\Lambda_{bottles}PM_j^y}{\text{InU}_{bottles,j}^{y}} \qquad (12)$$

Another example. The Packaging Labels Loss Indicator for a filler line can be established as:

$$\Lambda_{labels}PM_j^y = \sum_{p=1}^{production\ orders}\left[\text{InU}_{p,j}^{y} - \text{OtU}_{p,j}^{y}\right] \qquad (13)$$

Where all variables are expressed in number units and OtU_j^y is the Output Units for production line j during year y. In this case, $\text{InU}_{p,j}^{y}$ is set equal to the labels entering the production line j; the OEP Packaging Labels Loss indicator is then:

$$OEP(PML_{labels,j}^{y}) = \frac{\Lambda_{labels}PM_j^y}{\text{InU}_{labels,j}^{y}} \qquad (14)$$

As a good practice, it is desirable to directly count the packaging materials in the production line, using sensors and automated counters.

The **OEP Packaging Materials Loss Saving Benefit**, SBP_j^y, is determined by the equation:

$$\boldsymbol{SBP_j^y} = \left[OEP\left(PML_j^{base}\right) - OEP(PML_j^y)\right] \times \text{InU}_j^y \times PMC_j^y \qquad (15)$$

Where:

$OEP\left(PML_j^{base}\right)$ is the packaging material loss for production line j, during $base$ year.

$OEP\left(PML_j^y\right)$ is the packaging material loss for production line j, during year y.

SBP_j^y is the Saving Benefit in Packaging Materials Loss for production line j, year y.

PMC_j^y is the Packaging Materials Average Cost per unit for production line j, year y.

If the OEP Packaging Materials Loss Saving Benefit calculation results in a negative number, then the benefit represents a loss compared to the $base$ year. Packaging material prices manufacturing fluctuation is mitigated by subtracting the OEP Packaging Material Loss indicators first, and then multiplying it by the packaging materials average cost and output production.

3.5 OEP Maintenance Labour Extra Time indicator, $\boldsymbol{OEP(MLE)}$

Maintenance personnel are part of the manufacturing overhead cost (Silva et al. 2008). It is composed mainly of technicians in the areas of mechanics, electricity and automation. It is typical in the manufacturing sector to pay extra time to technicians to support maintenance activities off production hours (Salonen and Deleryd 2011). For example, industries that schedule one or two shifts per day might pay technicians extra time to support maintenance activities during the non-scheduled third shift, since the activities disrupt the production process.

As a factory achieves higher operational excellence levels, the facility will amass free time that could be used to schedule production-disrupting maintenance activities; thus, it will not be necessary to pay technicians for extra time since these activities could then be accommodated during the accumulated saved operational time. Hence, the overtime wages for maintenance technicians can be reduced as the facility saves time through the improvement in operational excellence levels.

The **OEP Maintenance Labour Extra Time indicator**, $OEP(MLE_j^y)$, ascertains the relationship between the maintenance labour extra time in line j in relation to output production. As the manufacturing facility achieves higher operational excellence levels, it is expected that the maintenance labour extra time is reduced as production shifts are diminished. The indicator is defined as:

$$\boldsymbol{OEP(MLE_j^y)} = \frac{\mathrm{MLE}_j^y}{\frac{TSd_j^{base}}{TSd_j^y} Prd_j^y} \qquad (16)$$

In man-hours divided by production units; production units can be expressed in number, volume (such as hectolitres) or weight (such as kilograms) units.

Where:

MLE_j^y is the Maintenance Labour Extra Hours for production line j during year y.

Prd_j^y is the output production, in production units, for production line j, during year y.

TSd_j^{base} is the theoretical speed for production line j, during the $base$ year.

TSd_j^y is the theoretical speed for production line j, during year y.

By incorporating the factor $\frac{TSd_j^{base}}{TSd_j^y}$, the OEP Maintenance Labour Extra Time indicator is compared in a better way to the base year.

As a good practice, the extra time for maintenance labour must be recorded with precision for each production line. Technicians must record the production line where the activity is taking place during the extra time.

The **OEP Maintenance Labour Extra Time Saving Benefit**, SBM_j^y, is determined by the equation:

$$\boldsymbol{SBM_j^y} = \left[OEP\left(MLE_j^{base}\right) - OEP\left(MLE_j^y\right)\right] \times Prd_j^y \times MEC_j^y \qquad (17)$$

Where:

$OEP\left(MLE_j^{base}\right)$ is the OEP Maintenance Labour Extra Time indicator for production line j and during the $base$ year.

$OEP\left(MLE_j^y\right)$ is the OEP Maintenance Labour Extra Time indicator for production line j and during year y.

MEC_j^y is the Maintenance Labour Extra Time Average Cost per man-hour for production line j during year y.

The Maintenance Labour Extra Time Average Cost per weight unit, MEC_j^y, must include wages, social costs and employee benefits. If the OEP Maintenance Labour Extra Time Saving Benefit calculation results in a negative number, then the benefit represents a loss compared to the base year.

3.6 OEP Maintenance Spare Parts indicator, $OEP(SPC)$

Spare parts, a critical element to support operational reliability (Wang 2012; Qiwei et al. 2018), are part of the manufacturing overhead cost. Spare parts are used during preventive and corrective maintenance of equipment on the shop-floor. Corrective maintenance is any unplanned maintenance performed to return equipment to proper working order, while preventive maintenance is a planned maintenance activity targeted to improve equipment life (Stenström et al. 2016). Preventive maintenance activities usually comprehend inspections, detection and correction of incipient failures, and scheduled maintenance to prevent equipment mal-functioning (Salonen and Deleryd 2011).

As the maintenance facility achieves higher operational excellence levels, it is expected that corrective maintenance is reduced while preventive maintenance is increased (Stenström et al. 2016). The cost benefit results are expected from the fact that preventive maintenance is usually less expensive than corrective maintenance.

The **OEP Maintenance Spare Parts indicator**, $OEP(MSP_j^y)$, establishes the relationship between the maintenance spare parts costs used in line j in relation to the output production. The indicator is defined as:

$$\boldsymbol{OEP(MSP_j^y)} = \frac{\mathrm{MSP}_j^y}{\frac{TSd_j^{base}}{TSd_j^y} Prd_j^y} \qquad (18)$$

In currency units divided by production units; production units can be expressed in counting, volume (such as hectolitres) or weight (such as kilograms) units.

Where:

MSP_j^y is the maintenance spare parts costs used by a production line j during year y.

Prd_j^y is the output production, in production units, for production line j, during year y.

TSd_j^{base} is the theoretical speed for production line j, during the $base$ year.

TSd_j^y is the theoretical speed for production line j, during year y.

By incorporating the factor $\frac{TSd_j^{base}}{TSd_j^y}$, the OEP Maintenance Spare Parts indicator is compared in a better way to the base year.

As a good practice, improvement projects costs must not be included in the maintenance spare parts costs, as well as other indirect maintenance costs such as trainings.

The **OEP Maintenance Spare Parts Saving Benefit**, SBS_j^y,is determined by the equation:

$$\boldsymbol{SBS_j^y} = \left[OEP\left(MSP_j^{base}\right) - OEP\left(MSP_j^y\right)\right] \times Prd_j^y \qquad (19)$$

Where:

$OEP\left(MSP_j^{base}\right)$ is the OEP Maintenance Spare Parts indicator for production line j and during $base$ year.

$OEP\left(MSP_j^y\right)$ is the OEP Maintenance Spare Parts indicator for production line j and during year y.

SBS_j^y is the Saving Benefit in Spare Parts for production line j and during year y.

This OEP indicator must be devalued to the actual currency value of year y, before determining the cost benefits. If the OEP Maintenance Spare Parts Saving Benefit calculation results in a negative number, then the benefit represents a loss compared to the base year.

4. Hypothetical case exercise

This section presents the application of the proposed OEP indicators through a hypothetical exercise to illustrate their usefulness and effectiveness in isolating the impact generated by fluctuations in manufacturing environments so that the cost benefits achieved through operational excellence in manufacturing operations can be determined. For the purpose of being succinct, the exercise only considers the OEP Energy Consumption indicator in two scenarios: one with same levels of operation excellence but with different production mix, and another with a higher level of operational excellence with different production mix and production schedule.

4.1 Scenario 1 (without OEP insight)

A manufacturing facility's production line operates for 240 hours of manned time per month, with the same level of operational excellence (based on OEE results per product), but with a different production, see Table 2. During both months, the production mix is comprised of the same two products {Product 1, Product 2}. The output production of Product 1 is 384 kg and of Product 2 is 358.4 kg during the base month. The production mix changes during the evaluation month since the output production of Product 1 is 768 kg and of Product 2 is 179.2 k g.

The Energy Cost per Output Production during the base month is $\frac{DLL\,\$315}{742.4\,Kg} = 0.42\,\frac{DLL\$}{Kg}$. While the Energy Cost per Output Production during the evaluation month is $\frac{DLL\,\$331}{947.2\,Kg} = 0.35\,\frac{DLL\$}{Kg}$.

Table 2. Cost efficiency due to changed production mix

Base Month:

During this month, the energy cost is DLL $315 for 2,205 energy units.

Two different products were manufactured:

	Theoretical Speed (kg/hour)	Manned Time (hours)	Manned OEE (hours)	Output Production (Kg))
Product 1	8.0	80.0	0.60	384.0
Product 2	4.0	160.0	0.56	358.4
Totals		**240.0**	0.60	**742.4**

Results: The energy cost per Kg is, DLL $315 ÷ 742.4 Kg, **0.42** DLL/Kg.

Evaluation Month:

During this month, the energy cost is DLL $331 for 2,317 energy units.

Same two products were manufactured, but with different manned time each and same OEE:

	Theoretical Speed (kg/hour)	Manned Time (hours)	Manned OEE (hours)	Output Production (Kg))
Product 1	8.0	160.0	0.60	768.0
Product 2	4.0	080.0	0.56	179.2
Totals		**240.0**	0.60	**947.2**

Results: The energy cost per Kg is, DLL $331 ÷ 947.2 Kg, **0.35** DLL/Kg.
Results: Thus, the energy cost per Kg improved compared to the base month.

The Energy Cost per Output Production improves in the evaluation month due to a production mix change without an increase in the shop-floor operational excellence (base on the OEE results). During the evaluation month, a product with a higher standard speed was produced for a longer time; note that the energy cost changes slightly since the machine production time is the same. Hence, the Energy Cost per Output Production does not show the cost impact of operational excellence.

4.2 Scenario 2 (Without OEP Insight)

The manufacturing facility's production line operates with a different production mix, with a higher level of Operational Excellence (based on OEE results per product) and with a different production schedule in the evaluation month, see Table 3.

During both months, the production mix is composed of the same two products {Product 1, Product 2}. The output production of Product 1 is 768 kg and of Product 2 is 179.2 kg during the base month. The production mix changes during the evaluation month since the output production of Product 1 is 280 kg and of Product 2 is 268.4 kg.

The Energy Cost per Output Production during the base month is $\frac{DLL\ \$331}{947.2\ Kg} = 0.35\frac{DLL\$}{Kg}$, Whereas the Energy Cost per Output Production during the evaluation month is $\frac{DLL\ \$210}{548.4\ Kg} = 0.38\frac{DLL\$}{Kg}$.

Table 3. Impact of production mix on operational excellence

Base Month:

During this month, the energy cost is DLL $331 for 2,317 energy units.

Two different products were manufactured:

	Theoretical Speed (kg/hour)	Manned Time (hours)	Manned OEE (hours)	Output Production (Kg))
Product 1	8.0	160.0	0.60	768.0
Product 2	4.0	080.0	0.56	179.2
Totals		**240.0**	0.60	**947.2**

Results: The energy cost per Kg is, DLL $331 ÷ 947.2 Kg, **0.35** DLL/Kg

Evaluation Month:

During this month, the energy cost is DLL $210 for 1,470 energy units.

Same two products were manufactured, but with different manned time each and better OEE:

	Theoretical Speed (kg/hour)	Manned Time (hours)	Manned OEE (hours)	Output Production (Kg))
Product 1	8.0	150.0	0.70	280.0
Product 2	4.0	110.0	0.61	268.4
Totals		**160.0**	0.60	**548.4**

Results: The energy cost per Kg is, DLL $210 ÷ 548.4 Kg, **0.38** DLL/Kg

Results: Thus, the energy cost per Kg did not improved compared to the base month.

From the Energy Cost per Output Production perspective, the manufacturing industry worsen the indicator although it operated with higher operational excellence, as the SKU production mix and production time schedule influences are combined. Hence, the Energy Cost per Output Production does not show the cost impact of operational excellence.

4.3 Scenario 3 (With OEP Insight)

In order to establish the cost benefits due to the factory operational excellence, the manufacturing facility uses the OEP Energy Consumption Indicator in Scenario 1, see Section 4.1.

Step 1: The effective theoretical speed of production for the base month, TSd_j^{base}, is calculated:

$$TSd_j^{base} = \frac{\left(8.0 \, {}^{Kg}/_{hrs} \times 80 \text{ hrs}\right) + \left(4.0 \, {}^{Kg}/_{hrs} \times 160 \text{ hrs}\right)}{240 \text{ hrs}} = 5.33 \, {}^{Kg}/_{hrs}$$

Step 2: The effective theoretical speed of production for the evaluation month, TSd_j^e, is calculated:

$$TSd_j^e = \frac{\left(8.0\,{}^{Kg}/_{hrs} \times 160\text{ hrs}\right) + \left(4.0\,{}^{Kg}/_{hrs} \times 80\text{ hrs}\right)}{240\text{ hrs}} = 6.66\,{}^{Kg}/_{hrs}$$

Step 3: The OEP Energy Consumption indicator for the base month, $OEP\left(ECp_j^{base}\right)$, is calculated:

$$OEP\left(ECp_j^{base}\right) = \frac{ECp_j^{base}}{\frac{TSd_j^{base}}{TSd_j^{base}} Prd_j^{base}} = \frac{2{,}205\text{ KW}}{\frac{5.33}{5.33} \times 742.4\text{Kg}} = 2.97\ KW/Kg$$

Step 4: The OEP Energy Consumption indicator for the evaluation month, $OEP\left(ECp_j^e\right)$, is calculated:

$$OEP\left(ECp_j^e\right) = \frac{ECp_j^e}{\frac{TSd_j^{base}}{TSd_j^e} Prd_j^e} = \frac{2{,}317\text{ KW}}{\frac{5.33}{6.67} \times 947.2\text{Kg}} = 3.06\ KW/Kg$$

Step 5: The energy saving benefit, SBE_j^e, is determined:

$$SBE_j^e = \left[OEP\left(ECp_j^{base}\right) - OEP\left(ECp_j^e\right)\right] \times Prd_j^e \times ECE_j^e \text{aaaaaaaaaaaaaaa}$$

$$SBE_j^e = \left[2.97\frac{KW}{Kg} - 3.06\frac{KW}{Kg}\right] \times 947.2\ Kg \times \frac{331DLL\$}{2317\ KW} = -DLL\ \$12.18$$

Considering the previous Scenario 1, the factor $\frac{TSd_j^{base}}{TSd_j^e}$ of 0.80 compensates the output production for the increase in the effective theoretical speed for month e. Now, the Saving Benefit in Energy is a loss of DLL -\$12.18, since it seems that there is no improvement in operational excellence, as the OEE metrics appoint, see Table 4.

Table 4. Actual cost benefit analysis through OEP indicator for Scenario 1

Base Month:

During this month, the energy cost is DLL $315 for 2,205 energy units.

Two different products were manufactured:

	Theoretical Speed (kg/hour)	Manned Time (hours)	OEE	Output Production (Kg)
Product 1	8.0	80.0	0.60	384.0
Product 2	4.0	160.0	0.56	358.4
Totals		**240.0**		**742.4**

Calculations: The energy cost per Kg is, DLL $315 ÷ 742.4 Kg, **0.42** DLL/Kg.

The effective theoretical speed is:

$$TSd_j^{base} = \frac{8\times 80 + 4\times 160}{240} = 5.33\,\frac{Kg}{hour}$$

The OEP Energy Consumption indicator is:

$$OEP\left(ECp_j^{base}\right) = \frac{ECp_j^{base}}{\frac{TSd_j^{base}}{TSd_j^{base}}\,Prd_j^{base}} = \frac{2{,}205\ \text{KW}}{\frac{5.33}{5.33}\times 742.4\text{Kg}} = 2.97\ KW/Kg$$

Evaluation Month:

During this month, the energy cost is DLL $331 for 2,317 energy units.

Same two products were manufactured, but with different manned time each and same OEE:

	Theoretical Speed (kg/hour)	Manned Time (hours)	OEE	Output Production (Kg)
Product 1	8.0	160.0	0.60	768.0
Product 2	4.0	80.0	0.56	179.2
Totals		**240.0**		**947.2**

Calculations: The energy cost per Kg is, DLL $331 ÷ 947.2 Kg, **0.35** DLL/Kg.

The effective theoretical speed is:

$$TSd_j^{e} = \frac{8\times 160 + 4\times 80}{240} = 6.67\,\frac{Kg}{hour}$$

The OEP Energy Consumption indicator is:

$$OEP\left(ECp_j^{e}\right) = \frac{ECp_j^{e}}{\frac{TSd_j^{base}}{TSd_j^{e}}\,Prd_j^{e}} = \frac{2{,}317\ \text{KW}}{\frac{5.33}{6.67}\times 947.2\text{Kg}} = 3.06\ KW/Kg$$

Results: While the energy cost per Kg improved compared to the base month, the OEP(ECp) shows no improvement due to Operational Excellence, as the constant OEE suggested.

In Scenario 1, there was no time saved since the OEE remained constant; therefore, the OEP Energy Consumption indicator did not show any cost benefits in Scenario 3.

4.4 Scenario 4 (With OEP Insight)

In order to establish the cost benefits due to the factory operational excellence, the manufacturing facility uses the OEP Energy Consumption Indicator in Scenario 2, see Section 4.2.

Step 1: The effective theoretical speed of production for the base month, TSd_1^{base}, is calculated:

$$TSd_j^{base} = \frac{\left(8.0^{Kg}/_{hrs} \times 160 \text{ hrs}\right) + \left(4.0^{Kg}/_{hrs} \times 80 \text{ hrs}\right)}{240 \text{ hrs}} = 6.66^{Kg}/_{hrs}$$

Step 2: The effective theoretical speed of production for the evaluation month, TSd_1^e, is calculated:

$$TSd_j^{e} = \frac{\left(8.0^{Kg}/_{hrs} \times 50 \text{ hrs}\right) + \left(4.0^{Kg}/_{hrs} \times 110 \text{ hrs}\right)}{160 \text{ hrs}} = 5.25^{Kg}/_{hrs}$$

Step 3: The OEP Energy Consumption indicator for the base month, $OEP\left(ECp_j^{base}\right)$, is calculated:

$$OEP\left(ECp_j^{base}\right) = \frac{ECp_j^{base}}{\frac{TSd_j^{base}}{TSd_j^{base}} Prd_j^{base}} = \frac{2{,}317 \text{ KW}}{\frac{6.66}{6.66} \times 947.2\text{Kg}} = 2.45\ KW/Kg$$

Step 4: The OEP Energy Consumption indicator for the evaluation month, $OEP\left(ECp_j^e\right)$, is calculated:

$$OEP\left(ECp_j^{e}\right) = \frac{ECp_j^{e}}{\frac{TSd_j^{base}}{TSd_j^{e}} Prd_j^{e}} = \frac{1{,}470 \text{ KW}}{\frac{6.66}{5.25} \times 548.4\text{Kg}} = 2.11\ KW/Kg$$

Step 5: The energy saving benefit, SBE_j^e, is determined:

$$SBE_j^e = \left[OEP\left(ECp_j^{base}\right) - OEP\left(ECp_j^e\right)\right] \times Prd_j^e \times ECE_j^e \text{aaaaiAAaaaaaaaaaa}$$

$$SBE_j^e = \left[2.45\frac{KW}{Kg} - 2.11\frac{KW}{Kg}\right] \times 548.4\ Kg \times \frac{210 DLL\$}{1470\ KW} = +DLL\ \$175.41$$

Considering the previous Scenario 2, the factor $\frac{TSd_j^{base}}{TSd_j^e}$ of 1.26 compensates the output production for the decrease in the effective theoretical speed for year e. Now, the Saving Benefit in Energy is DLL $175.41, since it seems that there is improvement in operational excellence, as the OEE metrics appoint for this case.

Table 5. Actual cost benefit analysis through OEP indicator for Scenario 2

Base Month:

During this month, the energy cost is DLL $331 for 2,317 energy units.

Two different products were manufactured:

	Theoretical Speed (kg/hour)	Manned Time (hours)	Manned OEE (hours)	Output Production (Kg))
Product 1	8.0	160.0	0.60	768.0
Product 2	4.0	080.0	0.56	179.2
Totals		**240.0**	0.60	**947.2**

Calculations: The energy cost per Kg is, DLL $331 ÷ 947.2 Kg, **0.35** DLL/Kg.

Results: The effective theoretical speed is:

$$TSd_j^{base} = \frac{8\times160+4\times80}{240} = 6.67\,\frac{Kg}{hour}$$

Results: The OEP Energy Consumption indicator is:

$$OEP(ECp_j^{base}) = \frac{ECp_j^{base}}{\frac{TSd_j^{base}}{TSd_j^{base}}Prd_j^{base}} = \frac{2{,}317\ \mathrm{KW}}{\frac{6.67}{6.67}\times947.2\mathrm{Kg}} = 2.45\ KW/Kg$$

Evaluation Month:

During this month, the energy cost is DLL $210 for 1,470 energy units.

Same two products were manufactured, but with different manned time each and better OEE:

	Theoretical Speed (kg/hour)	Manned Time (hours)	Manned OEE (hours)	Output Production (Kg))
Product 1	8.0	150.0	0.70	280.0
Product 2	4.0	110.0	0.61	268.4
Totals		**160.0**	0.60	**548.4**

Calculations: The energy cost per Kg is, DLL $210 ÷ 548.4 Kg, **0.38** DLL/Kg.

Results: The effective theoretical speed is:

$$TSd_j^{e} = \frac{8\times50+4\times110}{160} = 5.25\,\frac{Kg}{hour}$$

Results: The OEP Energy Consumption indicator is:

$$OEP(ECp_j^{e}) = \frac{ECp_j^{e}}{\frac{TSd_j^{base}}{TSd_j^{e}}Prd_j^{e}} = \frac{1{,}470\ \mathrm{KW}}{\frac{6.66}{5.25}\times548.4\mathrm{Kg}} = 2.11\ KW/Kg$$

Results: While the energy cost per Kg shows no improvement compared to the base month, the OEP(ECp) shows improvement due to Operational Excellence, as the increment in OEE suggested.

In Scenario 2, there was time saved since the OEE increased; therefore, the OEP Energy Consumption indicator shows cost benefit, see Table 5.

5. Case Study

This section presents the practical application of the proposed OEP indicators through an industrial case study in a major Food & Beverage manufacturer operating in Mexico City. The organisation produced 394,205.40 kg of finished product in their production line #1 during a base month, with an OEE of 37.5% and with an effective theoretical speed of production, TSd_1^b, of 40.57 kg/min.

During the evaluation month, the production line #1 produced 558,391.62 kg of finished product with an OEE of 41.2% and with an effective theoretical speed of production, TSd_1^e, of 39.22 kg/min.

The company's factory consumed electricity, water and bunker in this production line. The OEP indicators were calculated to determine the cost benefits regarding their operational excellence during the evaluation month, labelled *e*.

The **Saving Benefits for Electricity** were established as, SBE_1^e, from equations (3) and (4):

$$SBE_1^e = \left[OEP\left(ECp_1^{base}\right) - OEP\left(ECp_1^e\right)\right] \times Prd_1^e$$

$$SBE_j^e = \left[\frac{ECp_1^{base}}{\frac{TSd_1^{base}}{TSd_1^{base}} Prd_j^{base}} - \frac{ECp_1^e}{\frac{TSd_1^{base}}{TSd_1^e} Prd_1^e}\right] \times Prd_1^e$$

$$SBE_j^e = \left[\frac{\text{DLL \$9,502.91}}{\frac{40.57}{40.57} \text{394,205.40 Kg}} - \frac{\text{DLL \$4,310.26}}{\frac{40.57}{39.22} \text{558,391.62 Kg}}\right] \times \text{558,391.62 Kg}$$

$$SBE_1^e = \textbf{DLL \$9,292.37}$$

The factor ECE_j^y was dropped from equation (4) since the factory provided the electricity consumption, ECp_1^{base} and ECp_1^e, in DLL currency units instead of KWh.

Since ECp_1^e was provided in currency units, its value was devalued to the actual currency value of month *e*, before determining the saving benefit

The **Saving Benefits for Water** were established as, SBW_1^e from equations (3) and (4):

$$SBW_1^e = \left[OEP\left(WCp_1^{base}\right) - OEP\left(WCp_1^e\right)\right] \times Prd_1^e$$

$$SBE_j^e = \left[\frac{WCp_1^{base}}{\frac{TSd_1^{base}}{TSd_1^{base}} Prd_1^{base}} - \frac{WCp_1^e}{\frac{TSd_1^{base}}{TSd_1^e} Prd_1^e}\right] \times Prd_1^e$$

$$SBE_j^e = \left[\frac{\text{DLL \$4,713.04}}{\frac{40.57}{40.57} \text{394,205.40 Kg}} - \frac{\text{DLL \$5,461.00}}{\frac{40.57}{39.22} \text{558,391.62 Kg}}\right] \times \text{558,391.62 Kg}$$

$SBW_1^e = $ **DLL** $\mathbf{\$1,396.49}$

The factor ECE_j^y was dropped from equation (4) since the factory provided the water consumption, WCp_1^{base} and WCp_1^e, in DLL currency units instead of litres. Since WCp_1^e was provided in currency units, its value was devalued to the actual currency value of month *e*, before determining the saving benefit.

The **Saving Benefits for Bunker** were established as, SBB_1^e from equations (3) and (4):

$$SBB_1^e = \left[OEP\left(BCp_1^{base}\right) - OEP\left(BCp_1^e\right)\right] \times Prd_1^e$$

$$SBE_j^e = \left[\frac{BCp_1^{base}}{\frac{TSd_j^{base}}{TSd_1^{base}} Prd_1^{base}} - \frac{BCp_j^e}{\frac{TSd_j^{base}}{TSd_1^e} Prd_1^e}\right] \times Prd_1^e$$

$$SBE_j^e = \left[\frac{\text{DLL \$3,738.48}}{\frac{40.57}{40.57} 394{,}205.40 \text{ Kg}} - \frac{\text{DLL \$4,870.63}}{\frac{40.57}{39.22} 558{,}391.62 \text{ Kg}}\right] \times 558{,}391.62 \text{ Kg}$$

$SBB_1^e = $ **DLL** $\mathbf{\$586.89}$

The factor ECE_j^y was dropped from equation (4) since the factory provided the bunker consumption, BCp_1^{base} and BCp_1^e, in DLL currency units instead of kilograms. Since BCp_1^e was provided in currency units, its value was devalued to the actual currency value of month *e*, before determining the saving benefit.

The **Saving Benefits for the Direct Labour Used**, SBL_1^e, could not be determined since the factory did not record the number of persons at any given time in the production line. Hence,

$SBL_1^e = $ **DLL** $\mathbf{\$0.00}$

The **Saving Benefits for Raw Material Loss** are established as, SBR_1^e, from equations (8) and (9):

$$SBR_1^e = \left[OEP\left(RML_1^{base}\right) - OEP\left(RML_1^e\right)\ \right] \times Prd_1^e$$

$$SBR_1^y = \left[\frac{\Lambda RM_1^{base}}{Prd_1^{base}} - \frac{\Lambda RM_1^e}{Prd_1^e}\ \right] \times Prd_1^e$$

$$SBR_1^y = \left[\frac{\text{DLL \$27,872.67}}{394{,}205.40 \text{ Kg}} - \frac{\text{DLL \$47,029.65}}{558{,}391.62 \text{ Kg}}\ \right] \times 558{,}391.62 \text{ Kg}$$

$SBR_1^e = $ **− DLL** $\mathbf{\$7,546.68}$, a loss since the result is a negative number.

The factor RMC_j^y was dropped from equation (9) since the factory provided the raw material loss, ΛRM_1^{base} and ΛRM_1^e, in DLL currency units instead of kilograms. Since ΛRM_1^e was provided in currency units, its value was devalued to the actual currency value of month *e*, before determining the saving benefit.

The **Saving Benefits for** the **Packaging Material Loss** are established as, SBP_1^e:

$$SBP_1^e = \left[OEP\left(PML_1^{base}\right) - OEP(PML_1^e)\right] \times \mathrm{InU}_1^e \times PMC_1^e$$

The factory provided the Packaging Material Loss as the total sum of all packaging materials for production line #1 in DLL currency unit, instead of presenting the unit loss for each packaging material such as jars, labels, security seals and boxes. Hence, equation (12) could not be used and a similar formula to the Raw Materials Loss was used as an alternative.

$$SBP_1^e = \left[OEP\left(PML_1^{base}\right) - OEP(PML_1^e)\ \right] \times Prd_1^e$$

$$SBR_1^y = \left[\frac{\Lambda PM_1^{base}}{Prd_1^{base}} - \frac{\Lambda PM_1^e}{Prd_1^e}\ \right] \times Prd_1^e$$

$$SBR_1^y = \left[\frac{\text{DLL \$6,684.44}}{\text{394,205.40 Kg}} - \frac{\text{DLL \$11,601.79}}{\text{558,391.62 Kg}}\ \right] \times \text{558,391.62 Kg}$$

$SBP_1^e = \mathbf{-DLL\ \$2,132.90}$, a loss since the result is a negative number.

The factor PMC_j^y was dropped from equation (15) since the factory provided the packaging material loss, ΛPM_1^{base} y ΛPM_1^e, in DLL currency units instead of production units. Since ΛPM_1^e was provided in currency units, its value was devalued to the actual currency value of month *e*, before determining the saving benefit.

The **Saving Benefits for Maintenance Labour Extra Time** were established as, SBM_1^e, from equations (16) and (17):

$$SBM_1^e = \left[OEP\left(MLE_1^{base}\right) - OEP(MLE_1^e)\right] \times Prd_1^e \times MEC_1^e$$

$$SBM_1^e = \left[\frac{\mathrm{MLE}_1^{base}}{\frac{TSd_1^{base}}{TSd_1^{base}} Prd_1^{base}} - \frac{\mathrm{MLE}_1^e}{\frac{TSd_1^{base}}{TSd_1^e} Prd_1^e}\ \right] \times Prd_1^e \times MEC_1^e$$

$$SBM_1^e = \left[\frac{\text{17.0 man−hours}}{\frac{40.57}{40.57}\text{394,205.40 Kg}} - \frac{\text{33.10 man−hours}}{\frac{40.57}{39.22}\text{558,391.62 Kg}}\ \right] \times \text{558,391.62 Kg} \times 4.03 \frac{\text{DLL \$}}{man-hour}$$

$SBM_1^e = \mathbf{-DLL\ \$31.90}$, a loss since the result is a negative number.

The factor MEC_1^e was provided by the factory with a value of DLL $4.03 per man-hour during the month *e*.

The **Saving Benefits for Maintenance Spare Parts Costs** were established as, SBS_1^e, from equations (18) and (19):

$$SBS_1^e = \left[OEP\left(MSP_1^{base}\right) - OEP\left(MSP_1^e\right)\right] \times Prd_1^e$$

$$SBM_1^e = \left[\frac{\mathrm{MSP}_1^{base}}{\frac{TSd_1^{base}}{TSd_1^{base}}Prd_1^{base}} - \frac{\mathrm{MSP}_1^e}{\frac{TSd_1^{base}}{TSd_1^e}Prd_1^e}\right] \times Prd_1^e$$

$$SBM_1^e = \left[\frac{\text{DLL }\$4{,}713.04}{\frac{40.57}{40.57}394{,}205.40\text{ Kg}} - \frac{\text{DLL }\$5{,}461.00}{\frac{40.57}{39.22}558{,}391.62\text{ Kg}}\right] \times 558{,}391.62\text{ Kg}$$

$$SBS_1^e = \textbf{DLL \$2,960.76}$$

The Saving Benefits for Maintenance Spare Parts Costs was calculated as an example, since it made more sense to determine this benefit in a per year basis.

The Total Saving Benefits for this major Food & Beverage manufacturer for month *e* due to an increase in operational excellence, as suspected from the increase in OEE, were:

$$\text{Total Saving Benefits} = SBE_1^e + SBW_1^e + SBB_1^e + SBL_1^e + SBR_1^e + SBP_1^e + SBM_1^e + + SBS_1^e$$

Total Cost Bene fit = DLL $2960.76 for production line #1.

It was expected that there would be cost benefits, due to a high increment in the OEE indicator during the evaluation month. From the analysis, the OEP indicators that were more related to availability and performance time losses of OEE were the ones that showed cost benefits; and those OEP indicators that were more related to the quality yield losses of OEE, did not show cost benefits. This suggested that the improvement in OEE was due to an increment in the availability and performance factors. The manufacturing facility did not provide the values of the OEE factors.

6. Discussion, Concluding Remarks, Limitations and Further Research

For a firm to be competitive in the currently fast pace growing industrial era it is crucial to ensure that value adding features of operations are carefully determined and their outputs distinctly observed and assessed. This would contribute in defining how successful an enterprise has become as a consequence of formulating and implementing operational excellence strategies and initiatives. As a result, companies will have an ability to deploy the right performance improvements. For this purpose, a novel set of Operational Excellence Profitability (OEP) indicators has been proposed to assess the cost benefits of improvement activities in manufacturing processes. By doing this, this study fills a research gap, as previously discussed in Section 1, and contributes to the field of manufacturing performance measurement systems by:

- Developing a novel set of indicators which isolate the impact of fluctuations naturally embedded in manufacturing processes, e.g. variations in raw material prices, labour costs, production mix, production demands, and changes in the parameters of direct and indirect costs, which distort the cost benefit of operational excellence;
- Proving a set of indicators which manufacturing organisations can employ to conduct a systematic observation for in-depth analysis of operational performance using a structured approach that isolates manufacturing fluctuations so the results of operational excellence strategies and initiatives are not diluted. Additionally, the

proposed indicators can also be used to show the profitability potential in the short and long terms;
- Conducting a study which expands our knowledge and understanding of how best to measure the performance of manufacturing processes.

These contributions are beneficial for manufacturing organisations which aim at gathering information from the performance evaluation of their manufacturing processes so their directors and managers can take better decisions about how to manage those processes more effectively and efficiently. Due to the common need for accurately measuring operational and process performance, and in the same way in which OEE has been used in a wide range of manufacturing processes, all manufacturing sectors, e.g. automotive, aerospace, electronics, plastics, textile, etc. are likely to be able to employ the proposed OEP set of indicators, and hence benefit from this research.

Overall, the proposed OEP consists of six indicators: *(i)* OEP Energy Consumption Indicator, *(ii)* OEP Direct Labour Used Indicator, *(iii)* OEP Raw Materials Loss Indicator, *(iv)* OEP Packaging Materials Loss Indicator, *(v)* OEP Maintenance Labour Extra Time Indicator, and *(vi)* OEP Maintenance Spare Parts Indicator. A hypothetical case exercise and an industrial application of the proposed OEP indicators in a major Food & Beverage manufacturer based in Mexico City were carried out to provide guidance for their utilisation and demonstrate their effectiveness. The proposed OEP indicators would work best by comparing an evaluation period to a selected base year. In this case, the effects of manufacturing fluctuations are compensated by using the factors TSd and TSf and the difference of the indicators prior to the saving calculation. Through this compensation, the OEP indicators will show if there is a cost benefit to the implementation of improvement strategies not necessarily considered by other indicators, e.g. OEE. The proposed OEP indicators are not an extension of the OEE metric, which provide a measure of efficiency and yield for processes (Garza-Reyes 2015); rather, the OEP indicators provide a measure regarding cost benefits of improving operational excellence by isolating the impact of fluctuations in manufacturing processes. In practice, the use of the OEP metrics will not interfere with that of OEE, or vice-versa, as different performance elements are measured with the two. It will depend on a strategic decision for an organisation to decide whether to use one of these metrics alone or the two simultaneously.

In relation to the practical implications and limitations of the proposed metrics, first, due to the structural nature of the OEP indicators and performance elements considered for their calculation, their values will differ from those attained by other metrics, e.g. those of OEE. This advocates that OEP values cannot be directly compared to those of other metrics. Nevertheless, the proposed metrics can not only be used to present a ‘picture’ of the current state of production processes but also an ‘after improvements’ picture if the metrics are compared against itself through a ‘before’ and ‘after’ scenario. Secondly, even though the case study suggested that the data required to compute the proposed OEP indicators are easily available and collectable, which may make the proposed indicators an attractive alternative for some manufacturing organisations to assess the performance of their production processes, some considerations still need to be reflected upon to deploy them. This refers to the data collection procedures, information and calculations required to adopt the metrics. In this case, some organisations, especially those with a lack of established formal data collection procedures and information systems to measure their performance, may face important challenges for the implementation and use of the proposed OEP metrics. Thus, this issue may severely hinder the deployment of the OEP metrics in some organisations. This may be considered the major limitation of the proposed performance indicators. Thirdly, the case study presented in Section 5 indicated that the data needed to compute the OEP metrics can be collected by organisation's employees, whereas their calculation can be done through either the use of special purpose software packages or electronic spreadsheets. Fourthly, calculation routines for the OEP's various elements can be easily integrated as part of an organisation's existing management information and/or support decision-making systems to visualise OEP metrics and aid decision-making. With this, directors and managers would be able to take better decisions regarding how to best manage and improve the performance of their production processes and plant operations.

Despite the effectiveness of the indicators, proven through the hypothetical case exercise, see Section 4, and industrial case study, see Section 5, the limited validation of the proposed indicators through only these two cases can be considered as one of the limitations of this work. Thus, further research into the application of the OEP indicators in other industrial settings is recommended to gain a more robust validation of the indicators as well as to expand their depth and breadth. Similarly, future research can focus on expanding the reach of OEP metrics by considering the finished product perspective and other process elements, e.g. flexibility, dependability, speed, etc., which may also be considered important to measure the performance of production processes and plant operations. The incorporation of OEP metrics in visual-based analytical tools such as Value Stream Mapping (VSM) or the development of its own tools to map performance based on the OEP elements can also be considered as potential research streams derived from the work presented in this article.

Finally, the research has explicitly defined the necessity for the OEP indicators by identifying the missing link/gaps in existing indicators of manufacturing performance such as OEE and its extensions. The novelty of the proposed OEP indicators and their comprehensive approach to maximise the understanding of operational excellence can be of great value to both academics and practitioners for further research and application.

References

Al-Najjar, Basim. 1997. "Condition-Based Maintenance: Selection and Improvement of a Cost-Effective Vibration-Based Maintenance Policy for Rolling Element Bearings." Lund University. http://www.lunduniversity.lu.se/lup/publication/8658b1ad-5fab-4739-a449-b2f4tan

Aminuddin, Nur Ainunnazli Binti, Jose Arturo Garza-Reyes, Vikas Kumar, Jiju Antony, and Luis Rocha-Lona. 2016. "An Analysis of Managerial Factors Affecting the Implementation and Use of Overall Equipment Effectiveness." *International Journal of Production Research* 54 (15): 4430–4447.

Andersson, C, and M Bellgran. 2011. "Combining Overall Equipment Efficiency (OEE) and Productivity Measures as Drivers for Production Improvements." In *Swedish Production Symposium 2011*, 20–29. Lund, Sweden.

Andersson, C, and M Bellgran. 2015. "On the Complexity of Using Performance Measures: Enhancing Sustained Production Improvement Capability by Combining OEE and Productivity." *Journal of Manufacturing Systems* 35: 144–154.

Aspen, U., A-M. Brathen, P. G. Cassel, P. Ericsson, and M. Marelius. 1991. "Produktutveckling Inom Svenskt Naringsliv – En Studie Baserad Pa (In Swedish)." *In Hur Mata Produktivitet* 1.

Baines, Anna. 1997. "Productivity Improvement." *Work Study* 46 (2): 49–51.

Braglia, Marcello, Marco Frosolini, and Francesco Zammori. 2008. "Overall Equipment Effectiveness of a Manufacturing Line (OEEML): An Integrated Approach to Assess Systems Performance." *Journal of Manufacturing Technology Management* 20 (1): 8–29.

Braglia, M., Castellano, D., Frosolini, M., Gallo, M. 2018. "Overall material usage effectiveness (OME): a structured indicator to measure the effective material usage within manufacturing processes. " *Production Planning and Control* 29(2): 143-157.

Brandt, Loren, Johannes Van Biesebroeck, and Yifan Zhang. 2012. "Creative Accounting or Creative Destruction? Firm-Level Productivity Growth in Chinese Manufacturing." *Journal of Development Economics* 97 (2): 339–351.

Fernandes, Rui, Joaquim B. Gouveia, and Carlos Pinho. 2012. "Product Mix Strategy and Manufacturing Flexibility." *Journal of Manufacturing Systems* 31 (3): 301–311.

Garza-Reyes, Jose Arturo. 2015. "From Measuring Overall Equipment Effectiveness (OEE) to Overall Resource Effectiveness (ORE)." *Journal of Quality in Maintenance Engineering* 21 (4): 506–527.

Garza-Reyes, Jose Arturo, S. Eldridge, K.D. Barber, E. Archer, and T. Peacock. 2008. "Overall Resource Effectiveness (ORE) – an Improved Approach for the Measure of Manufacturing Effectiveness and Support for Decision-Making." In *Proceeding of the 18th International Conference on Flexible Automation and Intelligent Manufacturing*, 823–830. Skövde, Sweden, June 30-2 July.

Garza-Reyes, Jose Arturo, Steve Eldridge, Kevin D. Barber, and Horacio Soriano-Meier. 2010. "Overall Equipment Effectiveness (OEE) and Process Capability (PC) Measures: A Relationship Analysis." *International Journal of Quality & Reliability Management* 27 (1): 48–62.

Grünberg, Thomas. 2004. "Performance Improvement: Towards a Method for Finding and Prioritising Potential Performance Improvement Areas in Manufacturing Operations." *International Journal of Productivity and Performance Management* 53 (1): 52–71.

Hermel, Philippe, and Juan Ramis-Pujol. 2003. "An Evolution of Excellence: Some Main Trends." *The TQM Magazine* 15 (4): 230–243.

Hill, Terry. 2000. *Manufacturing Strategy*. USA: McGraw-Hill Higher Education.

Huang, Song, and Jun Yang. 2016. "Information Acquisition and Transparency in a Supply Chain with Asymmetric Production Cost Information." *International Journal of Production Economics* 182: 449–464.

Jaeger, A., K. Matyas, and W. Sihn. 2014. "Development of an Assessment Framework for Operations Excellence (OsE), Based on the Paradigm Change in Operational Excellence (OE)." *Procedia CIRP* 17: 487–492.

Kaplan, Robert S., and Robin Cooper. 1998. *Cost and Effect: Using Integrated Cost Systems to Drive Profitability and Performance*. Boston: Harvard Business School Press.

Kwon, Ohwoon, and Hongchul Lee. 2004. “Calculation Methodology for Contributive Managerial Effect by OEE as a Result of TPM Activities.” *Journal of Quality in Maintenance Engineering* 10 (4): 263–272.

Leung, Stephen C.H., Sally O.S. Tsang, W.L. Ng, and Yue Wu. 2007. “A Robust Optimization Model for Multi-Site Production Planning Problem in an Uncertain Environment.” *European Journal of Operational Research* 181 (1): 224–238.

Liu, Yifeng, and Jian Yang. 2015. “Joint Pricing-Procurement Control under Fluctuating Raw Material Costs.” *International Journal of Production Economics* 168: 91–104.

Muchiri, P., and L. Pintelon. 2008. “Performance Measurement Using Overall Equipment Effectiveness (OEE): Literature Review and Practical Application Discussion.” *International Journal of Production Research* 46 (13): 3517–3535.

Muthiah, K. M.N., and S. H. Huang. 2007. “Overall Throughput Effectiveness (OTE) Metric for Factory-Level Performance Monitoring and Bottleneck Detection.” *International Journal of Production Research* 45 (20): 4753–4769.

Nachiappan, R.M., and N. Anantharaman. 2006. “Evaluation of Overall Line Effectiveness (OLE) in a Continuous Product Line Manufacturing System.” *Journal of Manufacturing Technology Management* 17 (7): 987–1008.

Nakajima, Seiichi. 1988. *Introduction to TPM: Total Productive Maintenance*. *Productivity Press*. Portland, OR.

Oechsner, Richard, Markus Pfeffer, Lothar Pfitzner, Harald Binder, Eckhard Müller, and Thomas Vonderstrass. 2002. “From Overall Equipment Efficiency (OEE) to Overall Fab Effectiveness (OFE).” *Materials Science in Semiconductor Processing* 5 (4–5): 333–339.

Qiwei, Hu, John E. Boylan, Chen Huijing, and Ashraf Labib. 2018. “OR in Spare Parts Management: A Review.” *European Journal of Operational Research* 266(2): 395-314.

Olhager, J., Persson, F. 2006. “Simulating production and inventory control systems: a learning approach to operational excellence.” *Production Planning and Control* 17(2): 113-127.

Raja, P. Nelson, Soundararajan Kannan, and V. Jeyabalan. 2010. “Overall Line Effectiveness – a Performance Evaluation Index of a Manufacturing System.” *International Journal of Productivity and Quality Management* 5 (1): 38–59.

Raouf, A. 1994. “Improving Capital Productivity through Maintenance.” *International Journal of Operations & Production Management* 14 (7): 44–52.

Roghanian, Parastoo, Amran Rasli, and Hamed Gheysari. 2012. “Productivity Through Effectiveness and Efficiency in the Banking Industry.” *Procedia - Social and Behavioral Sciences* 40: 550–556.

Ron, A. J. De, and J. E. Rooda. 2006. “OEE and Equipment Effectiveness: An Evaluation.” *International Journal of Production Research* 44 (23): 4987–5003.

Roy, R., P. Souchoroukov, and E. Shehab. 2011. “Detailed Cost Estimating in the Automotive Industry: Data and Information Requirements.” *International Journal of Production Economics* 133(2): 694-707.

Salonen, Antti, and Mats Deleryd. 2011. “Cost of Poor Maintenance: A Concept for Maintenance Performance Improvement.” *Journal of Quality in Maintenance Engineering* 17 (1): 63–73.

Scott, Douglas, and Robert Pisa. 1998. “Can Overall Factory Effectiveness Prolong Moore’s Law?” *Solid State Technology* 41 (3): 75–82.

Sheu, D. Daniel. 2006. “Overall Input Efficiency and Total Equipment Efficiency.” *IEEE Transactions on Semiconductor Manufacturing* 19 (4): 496–501.

Silva, Carlos Manuel Inácio Da, Carlos Manuel Pereira Cabrita, and João Carlos De Oliveira Matias. 2008. “Proactive Reliability Maintenance: A Case Study Concerning Maintenance Service Costs.” *Journal of Quality in Maintenance Engineering* 14 (4): 343–355.

Stenström, Christer, Per Norrbin, Aditya Parida, and Uday Kumar. 2016. “Preventive and Corrective Maintenance – Cost Comparison and Cost–benefit Analysis.” *Structure and Infrastructure Engineering* 12 (5): 603–617.

Tan, H.T., Noble, J. 2007. “Plug and play (PnP) modelling approach to throughput analysis. ” *Journal of Manufacturing Technology Management* 18(7): 807-817.

Tomiura, Eiichi. 2007. “Foreign Outsourcing, Exporting, and FDI: A Productivity Comparison at the Firm Level.” *Journal of International Economics* 72 (1): 113–127.

Wacker, John G., Chen Lung Yang, and Chwen Sheu. 2006. “Productivity of Production Labor, Non-Production Labor, and Capital: An International Study.” *International Journal of Production Economics* 103 (2): 863–872. doi:10.1016/j.ijpe.2005.12.012.

Wang, Wenbin. 2012. “A Stochastic Model for Joint Spare Parts Inventory and Planned Maintenance Optimisation.” *European Journal of Operational Research* 216 (1): 127–139.

Wu, X.F., and G.Q. Chen. 2017. “Global Primary Energy Use Associated with Production, Consumption and International Trade.” *Energy Policy* 111: 85–94.

Wudhikarn, R. 2016. “Implementation of the Overall Equipment Cost Loss (OECL) Methodology for Comparison with Overall Equipment Effectiveness (OEE).” *Journal of Quality in Maintenance Engineering* 22 (1): 81–93.

Wudhikarn, R., C. Smithikul, and W. Manopiniwes. 2010. “Developing Overall Equipment Cost Loss Indicator.” Edited by G.Q. Huang, K.L. Ma, and P.G. Maropoulos. *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology. Advances in Intelligent and Soft Computing* 66. Berlin: 557–567.

Xu, Y., F. Elgh, J. A. Erkoyuncu, O. Bankole, Y. Goh, W. M. Cheung, P. Baguley, et al. 2012. “Cost Engineering for Manufacturing: Current and Future Research.” *International Journal of Computer Integrated Manufacturing* 25 (4–5): 300–314.

Zammori, Francesco. 2015. “Fuzzy Overall Equipment Effectiveness (FOEE): Capturing Performance Fluctuations through LR Fuzzy Numbers.” *Production Planning and Control* 26 (6): 451–466.

Zammori, Francesco, Marcello Braglia, and Marco Frosolini. 2011. “Stochastic Overall Equipment Effectiveness.” *International Journal of Production Research* 49 (21): 6469–6490.

Zhang, Guirong, and Zongjian Zhao. 2012. “Green Packaging Management of Logistics Enterprises.” *Physics Procedia* 24: 900–905.