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Research Article

A New Techno-Economic Real-Time Total Process Performance Indicator

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Abstract

Process performance measurement is a significant and crucial activity carried out by organizations aiming at controlling their processes. Most of the traditional performance indicators do not include important factors such as the effects of the external constraints on the process and do not emphasize the economic aspects influencing an organization. An organization's performance evaluation should measure both its efficiency and effectiveness, and not one or the other. The newly developed Total Process Performance (TPP) indicator is an integrated indicator that takes into account the process efficiency and effectiveness. This study modifies and integrates the efficiency and effectiveness of original formulae to create -for the first time- a customized new formula that includes important techno-economic factors representing a holistic overview of the process/organization performance. The study developed two indicators, a High (H) frequency indicator (early alarm), $TPP|_H$ which is calculated on hourly bases and intended for use by the floor managers, and a Low (L) frequency indicator, $TPP|_L$ that can be calculated for a longer period and intended to be used by top management. $TPP|_H$ reflects the shop floor's real-time performance based on internal factors, while $TPP|_L$ reflects the company performance based on internal and external factors. The differences between the newly developed indicators and the traditional indicators are illustrated. A real-time performance monitoring system is also developed. A case study for applying the new indicators in an iron-making plant is introduced.

Keyword: Process performance measurement; Effectiveness; efficiency; Real-time indicators

1. Introduction

The increase in competitiveness among companies has led to an increasing need for process and organization performance improvement. To attain these objectives, the process performance has to be measured, evaluated, and controlled (Viveros, 2018).

For example, measuring the performance in the healthcare sector is crucial. Yemane and coworkers (2021), worked on healthcare service performance analysis and improvement using discrete event simulation. They studied the patients' output, service rate, service efficiency, and their relation to the waiting time of patients in each service station, work in progress, and resource utilization. Vaezi, E. (2021), developed a Three-stage network model for measuring the performance of medical diagnostic laboratories to obtain the efficiency of the network, as interval efficiency in presence of an imprecise datum. They proposed a model that simulates the internal structure of a diagnostic lab using a criteria for evaluation obtained by the Fuzzy Delphi method. Berhan and coworkers (2018), Developed a model that investigates the performances of a general hospital and determines the optimum number of specialist doctors based on their respective workloads. To address this objective, the study developed a model using Arena Simulation Software that considers the real working environment and scenario of the general hospital. The study showed that there are unbalanced distributions in the daily workload among specialist doctors and extended long waiting times of patients in the hospital. The hospital was recommended to have a balanced workload distribution among specialist doctors and increase the number of specialist doctors by one or two in the fifteen service areas.

The process performance measurement is a very important task executed within an organization to evaluate the management performance and its quality (Pollalis and Koliousis, 2013). The performance improvement may be a result of good resource utilization and decreased losses and waste in the process. While the performance deficit may be a result of a lack of good resource utilization, which increases the process losses and waste. Every organization chooses many KPIs to measure the process performance. These indicators measure performance from different perspectives (Van Looy and Shafagatova, 2016)

The overall equipment effectiveness OEE is one of the performance measurement tools that measures and detects the process losses (Muchiri and Pintelon, 2008). The OEE is concerned only with discovering the losses in the production time, production speed, and production quality. Other process performance indicators may only measure asset effectiveness, production equipment effectiveness, or performance efficiency. This is why there is a need for an integrated indicator or a KPI to

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measure the overall process performance from different perspectives by one indicator. This indicator should allow the decision-maker to take the proper decision based on a quantitative measurement without judgmental evaluation to eliminate decision-making bias. Such an indicator should be used (BS EN 15341, 2019):
a) Measure the process's current status.
b) Compare (internal, external benchmarks, best practice).
c) Diagnose (analysis of strengths and weaknesses).
d) Identify objectives and define targets to be reached.
e) Plan improvement actions.
f) Continuously monitor changes over time.

1.1. Leading and lagging indicators

All processes have leading and lagging indicators. The process measures for the inputs indicators are the leading indicators, while the process measures for the outputs are the lagging indicators. Most of the performance measurement approaches concentrate on the lagging indicators, whereas the leading and lagging indicators contribute to the process's overall performance. This is why the suggested TPP will include both the lead and lag indicators. Including the leading indicators as a performance driver makes TPP a strong tool to trace the performance killers to eliminate them leading to a decrease in the performance deficiencies. Figure 1, shows the process leading and lagging indicators. (Muchiri and Pintelon, 2008).

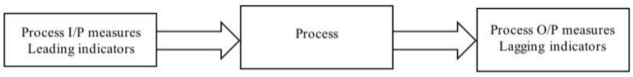

Fig 1. Leading and lagging indicators

1.2. Performance measurement criteria

The main purpose of performance measurement is to figure out the weaknesses and strengths in the process to take a suitable decision in the direction of strength improvement and weakness elimination. This is done with the objective of performance improvement to increase the organization's competitiveness and profits. Performance can be measured in three dimensions, according to the EN 15341:2007 standard (2019): technical, economical, and organizational. There are many types of process performance measurement indicators (Van Looy and Shafagatova, 2016), such as:

1. Efficiency Indicators
2. Effectiveness Indicators
3. Capacity Indicators
4. Productivity Indicators
5. Quality Indicators
6. Profitability Indicators
7. Competitiveness Indicators
8. Value Indicators

1.2.1. Efficiency Indicator vs. Effectiveness Indicators

Efficiency is the relationship between the *results* achieved, and the *resources* used, which means making things the best way possible using the least amount of resources. Effectiveness is the relationship between the *expected results* and the *obtained results*. The relationship between effective performance and efficient performance is shown in Fig 2.
One can say that *efficiency* is to be effective using a minimum of resources, focusing on the process and resources applied, for example, cost reduction. Effectiveness already focuses on the product and the obtained results and can bring benefits through higher profits (Adytia *et. al*., 2015).

1.3. Measuring the process performance using efficiency and effectiveness indicators

The most proper and available indicators on the operational management level and the functional management level are effectiveness and efficiency indicators. These indicators measure the management's effectiveness in objective achievement and its efficiency in resource utilization. These indicators will reflect on the other performance measurement indicators such as profitability, competitiveness, value indicator, etc. Therefore, this research will focus on measuring the process performance through the most suitable effectiveness and efficiency indicators combined. (Gackowiec et al., 2020).

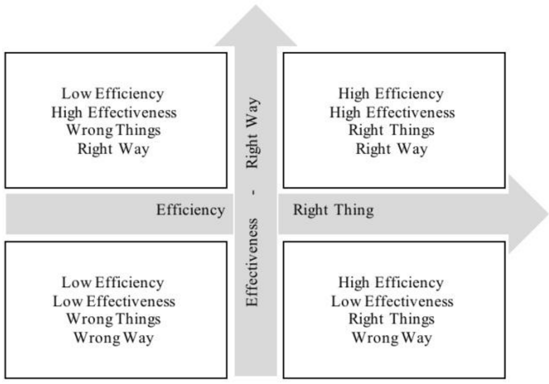

Fig 2. Effectiveness vs Efficiency (CIQA, 2021)

1.4. Research Problem and Objectives

Continuous feedback regarding the overall process performance including the internal and external factors at the top management and corporate level is vital for large organizations that practice close intervention in case of any objective deviation. Using the regular KPI systems keeps the management waiting till the quarterly, semi-annually or annual performance evaluation report is issued. This may be too late and considered old or off-line information. The issue is that it is extremely difficult to collect the required data from the process, perform calculations, analyze and report the results at small intervals or say in real-time. But still, there is a need for a systematic, comprehensive overall, and real-time indicator to allow taking a helicopter view of the process performance. Based on the results, a decision can be taken to improve the process in a reasonable time. In this context, a fast and easy calculated indicator is needed for front-line managers who manage the daily process activities enabling them to take action on time. As well as a less frequent indicator for top management to follow up on the overall organization's performance.

This work aims to find an effective process performance assessment tool by creating an overall performance indicator that contains most of the economic, and technical metrics. Creating an indicator for each management level is a suitable tool as a KPI for a more clear definition of responsibility and level actions.

The overall performance indicator will facilitate the following:

1. Evaluate the quality of each management level.
2. Discover any performance deficiency on time.
3. Take corrective action on time.
4. Give chance for a planned process improvement.
5. Discover surrounding process constraints.
6. Make all workers engaged in performance improvement as a target.

1.5. Research methodology

Step 1: Search all available effectiveness performance measurement indicators: Look for available indicators practically used to measure the process effectiveness and explain its formula.

Step 2: Search all available efficiency performance measurement indicators: Look for available indicators practically used to measure the process efficiency and explain its formula.

Step 3: Select applicable effectiveness and efficiency indicators: The selection needs to include the most indicative, unrepeated, and suitable measures to calculate the new indicators.

Step 4: Create an Integrated Indicator Formula that contains all the selected metrics: This is to represent the overall performance effectiveness and efficiency of the process. This indicator will be formulated in various ways to be suitable for different management levels.

Step 5: Select proper measurement intervals: The indicator measuring intervals have to be sensitive to detect any decline in performance, preferably at the same time. This will allow for a quick response to keep the performance near peak levels and intervene at the proper time.

Step 6: Develop a proper way for indicator visualization/monitoring: In this step, select the most proper way of data visualization by considering the nature of the data. (Viveros, 2018). Unfortunately, indicators that include a large number of variables are difficult to calculate at small intervals/high frequency due to a large amount of data processing required to obtain the final indicator value. In this case, it is preferable to keep the high-frequency indicator ($TPP|_H$) as simple as possible to make it easy to calculate. It is recommended to include a selection of the most important factors, which are monitored and controlled internally by the process managers.

In the case of the top management indicator, which is measured at a lower frequency ($TPP|_L$), still, the frequency should be fast and at close enough intervals to give the management a comprehensive, generalized, and fresh view of the internal and external factors that affect the organization performance and need to be monitored.

2. Literature Review

2.1. Performance effectiveness indicators

In this section, a review of available performance indicators which are used in performance measurement is presented. The most widely used one of these indicators is the OEE (Nakajima, 1998). Many measuring tools evolved from OEE, such as Total Equipment Effectiveness Performance (TEEP), Production Equipment Effectiveness (PEE), Overall Process Effectiveness (OPE), and Overall Asset Effectiveness (OAE). (Antosz and Stadnicka, 2014). The calculations for each indicator are summarized below.

2.1.1. Overall equipment effectiveness (OEE)

Total Productive Maintenance (TPM) is an approach to equipment maintenance that seeks perfect production with no unplanned breakdowns, no stops, no defects, and no accidents. (Muchiri and Pintelon 2008) TPM targets effective productivity by increasing uptime, reducing cycle time, and eliminating defects, (OEE 2021). The TPM eight pillars are mostly focused on proactive and preventive techniques for improving equipment reliability (Fabbri, 2019).

OEE is a TPM quantitative metric that identifies losses in the process due to unplanned stops, planned stops, small stops, slow cycles, production rejects and startup rejects, as shown in Table 1. (Muchiri, 2011). These losses are tracked by measuring the process availability, performance, and quality. Following are the OEE calculations.

Fully productive time = planned production time

Fully productive time = 0.85 of planned production time for OEE world-class organization

Table 1
TPM Calendar Hours Breakdown

<table>
<tr><td colspan="5">Total Time – Scheduled Time</td></tr>
<tr><td colspan="4">Planned Production Time</td><td>Scheduled Downtime, Scheduled Loss</td></tr>
<tr><td colspan="3">Run Time</td><td>Unplanned Downtime, Unscheduled Loss</td><td>Scheduled Downtime, Scheduled Loss</td></tr>
<tr><td colspan="2">Net Run Time</td><td>Slow Cycle, Small Stops, Performance Loss</td><td>Unplanned Downtime, Unscheduled Loss</td><td>Scheduled Downtime, Scheduled Loss</td></tr>
<tr><td>Fully Productive Time</td><td>Quality Defects Loss</td><td>Slow Cycle, Small Stops, Performance Loss</td><td>Unplanned Downtime, Unscheduled Loss</td><td>Scheduled Downtime, Scheduled Loss</td></tr>
</table>

$$OEE = Availability \,.\, Performance \,.\, Quality \quad (1)$$

$$Availability = \frac{Run\ Time}{Planned\ Production\ Time} \quad (2)$$

$$Performance = \frac{Actual\ Production\ Rate}{Planned\ Production\ Rate} \quad (3)$$

$$Quality = \frac{Total\ Conforming\ Production}{Total\ Actual\ Production} \quad (4)$$

- OEE = 100% is a perfect production.
- OEE = 85% is world-class for discrete manufacturing.
- OEE = 60% is fairly typical for discrete manufacturing.
- OEE = 40% is not uncommon for manufacturers without TPM and/or lean programs.

Whereas, lean management systems seek to decrease non-added value activities and wastes to reduce production costs (Ahuja and Khamba, 2008).

2.1.2. Total equipment effectiveness performance (TEEP)

TEEP was proposed by Invancic (1998). It is a performance metric that takes into account both equipment losses as measured by OEE and scheduled losses as measured by utilization. (Muchiri and Pintelon, 2008).

$$TEEP = Availability \,.\, Performance \,.\, Quality \,.\, Utilization$$

$$Utilization = \frac{Planned\ Production\ Time}{Total\ Time} \quad (5)$$

This metric is based on whether the demand is at or above plant production capacity, and measures continuous improvement in the process to decrease the scheduled delay time.

2.1.3. Production equipment effectiveness (PEE)

PEE was formulated by Raouf (1994) and is similar to OEE. The main difference is the allocation of weights to the various items in the overall effectiveness formula. (Muchiri and Pintelon 2008). The formula categorized the production types into:

a. Discrete production operations.
b. Continuous process operation.

-For discrete-type production operations:

$$PEE = (Availability)^{k1} \,.\, (Performance)^{k2} \,.\, (Quality)^{k3} \quad (6)$$

k_i - weight of indicator i, $0 < k_i \leq 1$, $\sum k_i = 1$

-For continuous process operations:

$$PEE = (Availability)^{k1} . (Attainment)^{k2} . (Performance)^{k3} . (Quality)^{k4} . (PSE)^{k5} . (OU)^{k6} \quad (7)$$

k_i - weight of indicator i, $0 < k_i \leq 1$, $\sum k_i = 1$

Production Equipment Effectiveness (PEE) formula for discrete-type production operations will be used as an effectiveness measurement indicator in the targeted overall indicator.

2.1.4. Overall process effectiveness (OPE)

OPE was developed to measure the factory level effectiveness. While OEE is about achieving excellence of individual equipment, OPE is about the relationships among different machines and processes as noted by Scott and Pisa (1998), and Muchiri (2008).

2.1.5. Overall asset effectiveness (OAE)

Overall Asset Effectiveness (OAE) and Overall Process Effectiveness (OPE) indicators are based on the OEE methodology. They have been designed to meet the specific requirements of different sectors and therefore appear in practice under different definitions. Of all the above indicators, they include the largest spectrum of calculated losses. It is used to identify and measure all losses associated with the entire production process. Both OAE and OPE have the same meaning in regards to the application of indicators in the industry but differ in the concept of production losses. OAE quantifies the production losses by output, while OPE by time (Muchiri and Pintelon 2008).

2.2. Performance efficiency indicators

The efficiency measure indicates how the management system utilizes all available resources and reduces waste and losses to decrease the cost of the final product, which should reflect positively on the profit margin.

2.2.1. Total process efficiency (TPE)

Total Process Efficiency (TPE) measures how well a process delivers products or services without generating waste. Increasing TPE requires constantly searching for ways to improve process performance by reducing the different types of waste. (BEM, 2021), (Al-Shaiba *et. al.*, 2019). Fig 3 shows the main TPE components.

$$Total\ Process\ Efficiency = (Utilization) . (Reliability) \quad (8)$$

$$Reliability=(Uptime). (Dependability) . (First\ Pass\ Yield) \quad (9)$$

$$Uptime = (Actual\ Run\ time)/(Scheduled\ Run\ Time) \quad (10)$$

$$Dependability = (Actual\ Run\ Rate)/(Design\ Run\ Rate) \quad (11)$$

$$First\ Pass\ Yield=(Good\ Outputs\ First\ Pass)/(Total\ Input) \quad (12)$$

$$Total\ Process\ Efficiency = \frac{Scheduled\ Hours}{Total\ Available\ Hours} \cdot \frac{Actual\ Run\ Time}{Scheduled\ Run\ Time} \cdot \frac{Actual\ Run\ Rate}{Design\ Run\ Rate} \cdot \frac{Good\ Output\ First\ Pass}{Total\ Input} \quad (13)$$

2.3. Other considered performance measurement factors

The efficiency indicators measure how the management system utilizes the available resources, whereas TPE measures only equipment utilization and reliability, which eliminates other important factors. TPE does not include how available resources are utilized such as:

1. Production resources utilization
2. Environmental impact
3. Energy utilization
4. Human resources utilization
5. Safety measures

In addition to the TPE indicator metrics, other factors such as operation cost, process environmental impact, production per head, energy utilization, and safety should be considered.

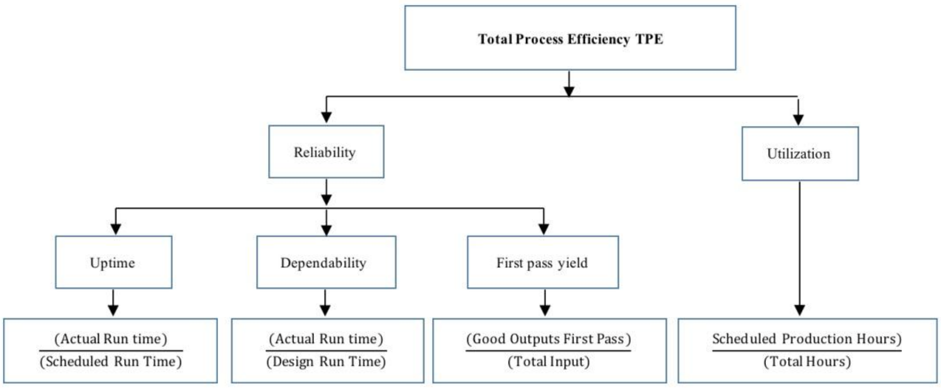

Fig 3. Total Process Efficiency TPE components

2.3.1. Production resources utilization factors

This metric measures the most common and effective *cost indicators* like maintenance cost utilization, raw material utilization, and consumed utility utilization. These costs represent the highest share of the final product cost. Each of these costs will be calculated as a ratio, each value will be compared to a reference to get the ratio. In case a reference is unavailable or there are any constraints to using a benchmark and best practices as a reference, the Program Evaluation and Review Technique (PERT) formula will be used instead. PERT combines probability theory and statistics to derive a formula for the average activity from a three-point estimate.: Optimistic (O), Most Likely (M), and Pessimistic (P). PERT estimate formula is: (O + 4M +P) / 6. PERT calculates a reference value from the process historical data as it is more representative of the process performance and is achievable (Enste and Gmbh, 2017). PERT formula will be adjusted as follows:

$$PERT\ Reference\ Estimate = [Maximum\ value + (4 \times Mean\ value) + Lower\ value]/6 \quad (14)$$

2.3.2. Maintenance Cost Utilization Factor

This metric calculates the actual maintenance cost per ton of final product using the PERT estimation technique.

$$Maintenance\ Cost\ Utilization = \frac{\left[\frac{Highest\ cost + 4xMean\ cost + Lower\ cost}{6}\right]}{Actual\ maintenance\ cost} \quad (15)$$

The highest maintenance cost per ton of final product, mean maintenance cost per ton of final product, and lowest maintenance cost per ton of final product should be calculated from the available process historical data (Stenström et al. 2013).

- The actual maintenance cost reference is calculated from the historical data for the same intervals of the period under study either monthly, quarterly, or semiannually.
- Reference value will be changed based on the period of historical data considered.

2.3.3. Raw material utilization factor

This metric calculates how the process efficiently utilizes all the input raw materials compared to theoretical material input to produce one unit of the final product. Theoretical raw material input is the estimated amount of raw materials that are used to calculate the unit output.

$$Raw\ Material\ Utilization\ Factor = \sum_{1}^{n} \frac{theoretical\ materials\ I/P\ per\ unit\ of\ final\ product}{actual\ material\ I/P\ per\ unit\ of\ the\ final\ product} \quad (16)$$

n: Refers to the number of raw materials

- If the actual value = the theoretical value, the utilization factor will be 1.
- If the actual value < the theoretical value, the utilization factor will be > 1, which will lead to increasing the Total Process Performance (TPP).
- If the actual value > the theoretical value, the utilization factor will be < 1, which will lead to decreasing the Total Process Performance (TPP).

2.3.4. Utilities utilization factor

This metric measures how floor management utilizes consumed utilities as low as possible to decrease utilities consumption per ton of final product, which will reflect on the cost of the final product.

$$Utilities\ Utilization\ Factor = \sum_{1}^{m} \frac{actul\ CO_2\ emissions\ per\ unit\ of\ final\ product}{actual\ CO_2\ emissions\ per\ unit\ of\ the\ final\ product} \quad (17)$$

m: refers to the number of utilities

2.3.5. Environmental Impact Factors

The environmental impact indicators are ethical performance measurement factors. They depend on the organizational culture and beliefs. This is why, most countries have regulations for industrial emissions and hazardous wastes, which have significant harmful impacts on the environment.

2.3.6. CO_2 emissions factor

The production process should not adversely affect the environment, therefore there is a worldwide effort toward the reduction of harmful industrial emissions to decrease the global warming effects. Most of the companies whose production process involves CO_2 emissions (like the one under study) usually have an objective of CO_2 emissions reduction. In this research, the below metric will be used for measuring the CO_2 emission factor, to have the CO_2 reduction as one of the process managers' objectives as a measure for the environmental impact. Any objective has to be SMART (Specific, Measurable, Achievable, Realistic, and Time-bound). The comparison will be against the theoretical or nominal emission value for the process. The calculated theoretical emission value is process specific.

$$CO_2\ Emission\ Factor = \sum_{1}^{k} \frac{Thrortical\ CO_2\ emission\ per\ unit\ of\ product}{actual\ CO_2\ emission\ per\ unit\ of\ the\ product} \quad (18)$$

k: refers to the number of processes emitting CO_2

2.3.7. Environmental hazard waste factor

Furthermore, any hazardous waste has to be decreased as possible. This is why the environmental impact included also a metric to mitigate the hazard waste impact on the environment to make it as low as possible.

$$Environmental\ Hazard\ Waste\ Factor = \frac{Lowest\ waste\ generated\ per\ ton\ of\ final\ product}{actual\ waste\ generated\ per\ ton\ of\ final\ product} \quad (19)$$

In equation 19 and to realize the good effect of minimizing the hazard waste of the process, the actual waste generated was referenced to the lowest waste generated during the period under study. This means, that the more the actual waste generated, the lower the hazard factor, which will lead to decreasing the TPP.

2.3.8. Energy utilization factor

The process has to utilize all available energy resources rationally. The most popular energy resources are electric and fuel energy, which are converted in most cases to the required mechanical power or heat needed for production. For example, in case of an over consumption of electrical power, this would be an indication of low equipment efficiency on the energy side. The fuel consumption to produce heat energy is another example of energy needed to be utilized efficiently, which will be reflected in the process performance.

$$Energy\ Utilization\ Factor = \sum_{1}^{L} \frac{Theoretical\ energy\ consumption\ per\ unit\ of\ product}{actual\ energy\ consumption\ per\ unit\ of\ the\ product} \quad (20)$$

L: refers to the number of energy resources

2.3.9. Human resources utilization

The production labor is one the most relevant resources to production output, therefore, efficient utilization of this resource increases the performance of the process.

$$Production\ Labor\ Utilization = \sum_1^P \frac{(Actual\ man{-}hour)}{(Actual\ production\ )} / \frac{(Available\ man{-}hour)}{(Capacity\ \ of\ production\ )} \quad (21)$$

P: refers to the number of final products

- *Actual man-hour = number of labor (contributing to the final production) x number of working hours per study period.*
- *Actual production = total units produced of final product per study period.*
- *Available man-hour = number of process labor x number of calendar hours per study period.*
- *Capacity of production = total units of the final product at full capacity per study period.*

Fig 4 shows the modified TPE to be mapped to TPP indicator components.

3. The New Total Performance Measurement Formula

In the effort to develop an integrated performance measurement formula, the suitable performance evaluation indicators will be integrated into one formula which contains the lead and lag performance indicators. This Total Process Performance (TPP) indicator is a ratio-based indicator. The developed indicator will have two versions based on the frequency of measurement, namely $TPP|_H$ and $TPP|_L$ as will be explained. (Neely at. el. 2005).

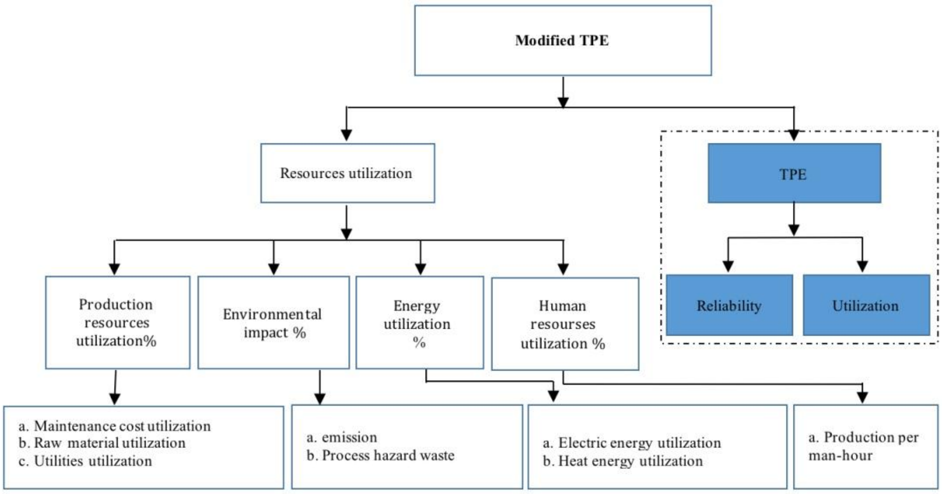

Fig 4. Modified TPE mapped to TPP indicator components

3.1. Indicator for process managers $TPP/_H$

The $TPP|_H$ indicator will be used to keep the process management staff or floor managers at different functions informed in real-time about the process performance to take corrective action on time. The subscription "H" refers to "High" frequency, as this indicator is calculated in our case every hour. This indicator will include only the factors under the process management control, where they can make the required process adjustment to attain the target level of this indicator. The frequency of calculation for this indicator should give the floor managers a glance at the process dynamics in real-time. This indicator should be simple, easy to calculate, and contains only the most important production parameters related to output, availability, quality, and utilities. The selection of the parameters should reflect their importance to the floor managers based on the criterion set by them. This indicator will be based on historical process baseline data for the measured factors as a reference. Actual dynamic/real-time data will be calculated as a percentage in comparison to the baseline data. Fig 5 shows the $TPP|_H$ indicator components.

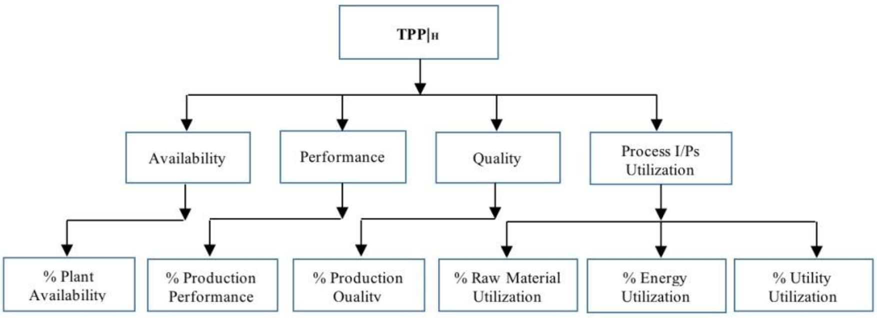

Fig. 5. $TPP|_H$ indicator components

The $TPP|_H$ factor is composed of two contributors, effectiveness and efficiency parts. The fast calculated effectiveness factor will be named "dynamic effectiveness", and the fast calculated efficiency factor will be named "dynamic efficiency". The baseline will resemble the planned production parameters, which may change for example every month, based on the annual production plan and the monthly plan dynamics for the department.

This indicator includes a baseline for all process measured factors as a reference and the actual dynamic readings are calculated from the data acquisition system as a percentage compared to the baseline. Table 2 lists the baseline parameters, which are divided into effectiveness and efficiency factors table. The table is an example of implementing the $TPP|_H$ in an Iron Direct Reduction Plant (DRP) process.

$$TPP|_H = \text{Process Dynamic Effectiveness} \cdot \text{Process Dynamic Efficiency} = (Performance_a / Performance_b)^{w1} \cdot (Availability_a / Availability_b)^{w2} \cdot (Quality_a / Quality_b)^{w3} \cdot (\text{Raw material utilization}_b / \text{Raw material utilization}_a)^{w4} \cdot (Utility_{b1} / Utility_{a1})^{w5} \ldots\ldots (Utility_{b(n-1)} / Utility_{a(n-1)})^{w(k-1)} \cdot (Utility_{bn} / Utility_{an})^{wk} \quad (21)$$

Table 2
Baseline parameters

Component	Process Dynamic Effectiveness			Process Dynamic Efficiency Process Resources Utilization Process Utilities		
	Performance	Availability	Quality	Raw Material Utilization	Energy	Utility

- '*a*' stands for actual, and '*b*' stands for base, '*k*' and '*n*' are numbering constants.
- All utility consumptions are calculated per ton of production.
- Effectiveness metrics calculation will be (actual value/baseline value), as the objective is to measure how the actual value is compared to the baseline. The target is to increase the actual as possible to be near or higher than the baseline value.

The efficiency metrics calculation will be (baseline value /actual value), as the target is to measure how the actual value is compared to the baseline. The target is to decrease the actual value as possible to be near or lower than the baseline value. In case the value was >1, it will be taken as 1.

- Relative weights or power values, $0 < w_i \leq 1$, will be decided by the process experts to align the results with the organization's strategy.
- The equation can be tailored to the organization's needs, for example by considering only the high process utilities consumption and eliminating the low consumption.

3.2. *Top management indicator (lower frequency indicator) $TPP|_L$*

The performance measurement indicator for top managers, $TPP|_L$ has to include metrics that are of interest for top management functions; such as (operations, maintenance, quality, human resources, market, and other functions) as shown in Fig 6.

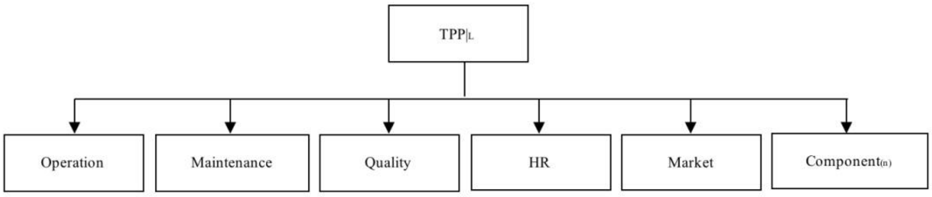

Fig. 6. $TPP|_L$ indicator components

The subscription "L" refers to "Low" frequency, as this indicator is calculated for example every month. $TPP|_L$ will include inbound and outbound metrics, which measure the effect of the internal organization's factors as well as external factors' effects on the process performance. As the outbound factors are coming from outside the organization, they are out of the monitoring scope of the shop floor management and only the top management may be concerned with these factors. This indicator will not be calculated in this paper as it needs an extended time to gather the data and draft its control chart, it will be the subject of a subsequent paper.

3.2.1. Operation performance indicator

It is a very important indicator that has to be included in production management performance evaluation, it is related to productivity and utility consumption. The production management system in any organization seeks to produce the maximum product output with the lowest cost and lowest utility consumption to have a competitive product.

3.2.2. Maintenance performance indicator

One of the vital indicators from the maintenance management point of view with a target to keep the process running with the lowest number of stoppages or breakdowns.

3.2.3. Maintenance cost utilization

In addition to the maintenance performance indicator, a maintenance cost utilization indicator is important to be considered as a measure of how efficient the maintenance management system is cost-wise. Maintenance cost utilization has to be calculated based on a relative value. This value determines how the actual maintenance cost is compared to a best practice or a reasonable reference maintenance cost. (Alsyouf, 2006), (Ben-Daya, 2009). The PERT method can be used to get an estimated reference cost number (Parida, 2007).

3.2.4. Equipment availability

The simple equation of availability calculation in OEE can be considered as the equation used for calculating this indicator.

$$Availability = \frac{Run\ time}{planned\ Production\ Time}$$

3.2.5. Quality performance indicator

The simple equation of quality yield calculation in OEE can also be considered as the equation used for calculating this indicator.

$$Quality = \frac{Total\ Conforming\ Production}{Total\ Actual\ Production}$$

3.2.6. Safety Performance Indicator

The safety of people is the most important indicator that has to be monitored and controlled on all organizational levels by controlling the process hazards and eliminating the risks and providing the proper protective equipment. This indicator reference target should be zero injuries and zero safety issues. This indicator will not be included in the overall indicator calculations and will be presented separately because it should not have a target value that is more than zero as all organizations should seek to make this indicator always at a zero value.

3.2.7. Human resources indicator

The most human resources indicator related to production is how much an employee contributes to the final product amount (Al-Shaiba *et. al.*, 2019).

3.3. Proper measures interval selection

The $TPP|_H$ indicator formula can be calculated hourly, per shift, or daily, based on the process control system capability and IT infrastructure that retrieves the indicator's data. In this study, $TPP|_H$ is calculated hourly as shown in the case study.
The indicator $TPP|_L$ formula can be calculated weekly, monthly, or semiannually. This depends on the interconnection between the data collected from the control system and the data collected from the Enterprise resource planning (ERP) system. In this study, it is suggested to measure the $TPP|_L$ monthly.

3.4. Proper method for indicators visualization

There are many ways for data visualization such as; trends, bar charts, and different types of control charts. The control chart is the most suitable way of visualizing short-term variations of the TPP indicators. Control charts limits should be recalculated regularly to avoid comparing the indicators with fixed reference values as it may be unfair due to several reasons:

1. Conditions that contributed to achieving this reference value may be different from the conditions during the process evaluation interval.
2. Process capability may change due to production assets aging.
3. The reference value is dependent on process inputs which vary from time to time.
4. Control charts enable the distinguishing between process variations resulting from common and special causes. Fig 7 shows the detailed $TPP|_L$ components.

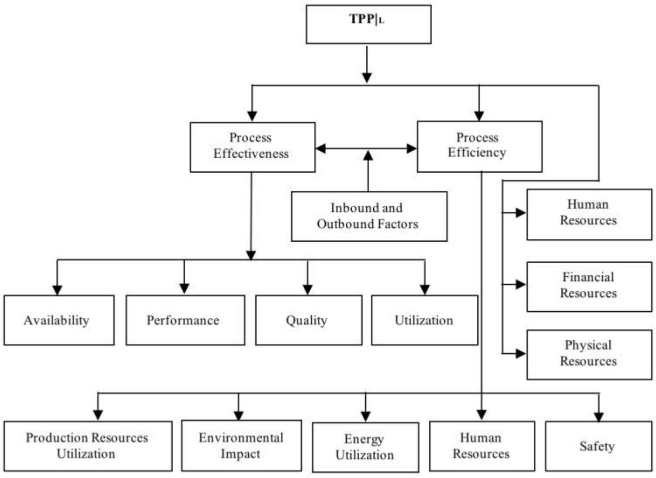

Fig. 7. The detailed $TPP|_L$ components

4. Case Study And Implementation

The case study is applied to an iron direct reduction plant. A process in a steel production plant was selected to implement the new performance evaluation technique. The practical implementation methodology for $TPP|_H$ (and $TPP|_L$ later) is systematic as shown in Fig 8.

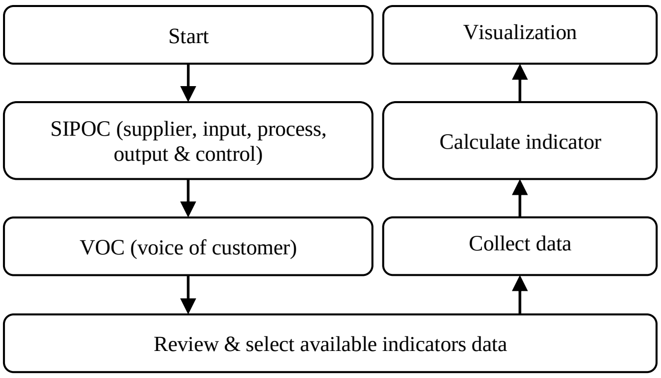

Fig. 8. Implementation methodology for $TPP|_H$ and $TPP|_L$

4.1. Implementation steps

1. *Determine the process under performance evaluation*

   In this step, the process under study needs to be identified with sufficient knowledge about its theory of operation, process components, the function of each component, final product specifications, final product quality, operation procedure, and parameters.
2. *Identify the process inputs and make SIPOC ((supplier, input, process, output, and control) (Nonthaleerak and Hendry, 2006)*

In this step the following information has to be identified:

- All process inputs and their consumptions per unit of the final product
- The raw material suppliers and their specifications
- The process operations and their component functions
- The process outputs and their specifications and quality measures
- The process control parameters
- The process customers and their requirements

3. *Set required objectives from the voice of the customer*
   The process internal and external customers have to be identified clearly to customize the performance indicator metrics that can measure his requirements to attain the customer satisfaction.
4. *Review and select all available indicators*
   Review the performance indicator metrics to be adapted, then add or remove metrics to fit the nature of the process under study.
5. *Set the measurement interval based on plant IT capabilities and speed of operations*
   TPP$|_H$ needs to be calculated with a high frequency (small intervals) to be valuable and to provide dynamic feedback in real-time for the process managers.
   For the TPP$|_L$, the frequency of calculation will depend on the management requirements. The recommended calculation interval may be weekly or maximum monthly, based on the IT capability, the process data acquisition system capability on storing and retrieving data, and the system dynamics.
6. *Collect the required data*
   The required data for indicator calculation are to be collected and stored through the process IT system in a proper database (Azizi, 2015).
7. *Make required calculation*
   Calculate the indicator formula with the available data processing software.
8. *Visualize the results*
   TPP$|_H$ should be visualized in a proper way to make it available in real-time to all concerned process managers (Viveros, 2018). TPP$|_L$ needs to be visualized properly and its terms have to be explained and any improvement or decline has to be justified to top management.
9. *Take the required action (eliminate, mitigate, accept) based on the indicator value*
   Based on the calculation results of the specific indicator, the concerned function has to take suitable action, which can be:
   - Eliminate the source of low performance, for example in the case of a faulty machine; apply a maintenance action.
   - Mitigate source of low performance if a process input is out of specifications.
   - For example, Accept low performance in case of low demand or raw material supply shortage.

4.2. TPP$/_H$ implementation in an iron direct reduction plant

During the case study, TPP$|_H$ was calculated for an iron direct reduction plant (DRP) process. Firstly, the direct reduction process will be briefly introduced, then the methodology of implementation will be presented.

4.2.1. The DRI process

The direct reduction process is a production process where the Oxygen is removed from the low iron content ore which has about 67% Fe, through a direct reduction process to produce a higher iron content material of 95% Fe, to be used in the melt shops as a raw material to produce high-quality molten steel and the final product (flat/rebar).

4.2.2. Identify the direct reduction process SIPOC

In this step, the process input internal suppliers will be determined as well as, production process details, process output, and process output internal customers.

4.2.3. Process value stream mapping VSM

The value stream mapping represents the production process flow in terms of blocks to identify the added value processes and the process bottlenecks. A bottleneck is a performance killer, so it has to be monitored to make the necessary improvement on time to keep an acceptable process performance. An example of the VSM for a direct reduction plant is shown in Fig 9, it highlights the Oxide Reduction as a process bottleneck that has the lowest production rate of 140 t/h. This bottleneck affects the performance matrix, effectiveness, and production rate.

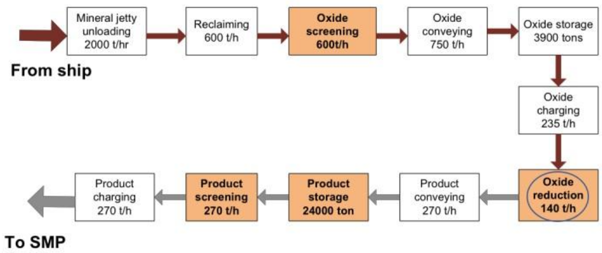

Fig 9. VSM for direct reduction plant

4.2.4. Process inputs

In this step, all the inputs to the direct reduction plant to produce one ton of DRI are listed. Fig 10 shows the direct reduction process inputs of utilities and raw materials per ton of final product.

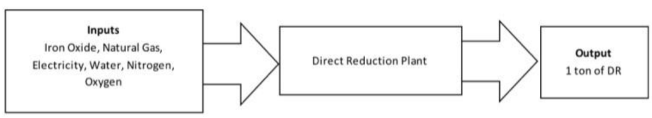

Fig 10. Direct reduction process inputs and outputs

4.2.5. DRI plant objectives from the viewpoint of the internal voice of the customer

The process objectives are to achieve the highest productivity with optimum quality and the lowest cost while preserving the resources to increase both the efficiency and effectiveness of the process.

4.2.6. Available indicators

The indicator $TPP|_H$ (and later the $TPP|_L$) can be used as performance measurement indicators for the DRI process. The measurement interval for performance measurement indicators are:

1. $TPP|_H$, to be calculated every hour.
2. $TPP|_L$ is recommended to be calculated every week.

4.2.7. Data collection and calculation of $TPP/_H$

The data reading rate for the formula variables was one reading per hour. Traditionally, the collected data is extracted from the plant control system that records the process variables, then the recorded data is saved in a separate excel sheet for processing. This process may take one day to extract the data and record it, a process that depends on the capabilities of the available control system. The difficulty of extracting the data is in the time it takes to convey this data accurately from the control system to the external Microsoft Excel spreadsheet format. This is why the traditional way may not be fast enough to give timely feedback on the process performance. When calculating this indicator for the DRP process, the new formula was impeded in the Distributed Control System (DCS), which makes the calculation automatic, fast, without human intervention, and in real-time. Applying formula (21) gives:

$TPP|_H$ = *Process Dynamic Effectiveness . Process Dynamic Efficiency*$=(Performance_a/Performance_b)^{1.0} . (Availability_a/Availability_b)^{0.7} . (Quality_a/Quality_b)^{1.0} . (Raw\ Material\ Utilization_b/Raw\ Material\ Utilization_a)^{0.6} . (NG_b/NG_a)^{0.5} . (Water\ Consumption_b/Water\ Consumption_a)^{0.3} . (Electricity_b/Electricity_a)^{0.2} . (Oxygen_b/Oxygen_a)^{0.01} . (Nitrogen_b/Nitrogen_a)^{0.01}$

Where, the powers of formula (21) are as follows: $W_1=1.0$, $W_2=0.7$, $W_3= 1.0$, $W_4=0.6$, $W_5=0.3$, $W_6=0.2$, $W_7=0.01$ *and* $W_8=0.01$. The power of each metric is estimated by the process experts and the process management committee. In this example, the utilities used were: Natural Gas (NG), water, electricity, Oxygen, and Nitrogen. Table 3 is an example of the daily collected and calculated data for calculating the $TPP|_H$ indicator. All utility consumptions are calculated per ton of the final product. (Tsarouhas, 2019).

4.2.8. Process performance visualization

To visualize the real-time changes of the $TPP|_H$ indicator and to take the required response on time, the data was displayed on a control chart in different places on the shop floor. Table 4, shows a sample of the control chart calculated values, the red colors denote outlier values. Fig 11 shows a sample control chart for $TPP|_H$ for a 3-shifts working day.

Control chart calculations:

Standard Deviation, $\sigma = \sqrt{\frac{\sum_i^N |x_i-\mu|^2}{N}}$ (22)

Where $\sum$ is the sum of the individual values (x_i) in the data set, μ is the mean of the data set, and N is the number of data points in the population.

Table 3
Example of collected and calculated data

		Effectiveness			**Efficiency**					
	Baseline values	**Performance**	**Availability**	**Quality**	**raw material**	**Natural gas**	**Water**	**Electricity**	**Oxygen**	**Nitrogen**
Base Line Values	Item	120.000	0.990	0.990	1.530	297.600	0.830	0.104	11.800	14.300
	Unit	ton/hr	%	%	%	m3/ton	m3/ton	kW.h/ton	m3/ton	m3/ton
	Power	w1	w2	w4	w6	w7	w8	w9	w10	w11
	Suggested value of w	1.000	0.700	1.000	0.600	0.500	0.300	0.200	0.010	0.010
	Actual average values	**Performance**	**Availability**	**Quality**	**raw material**	**Natural gas**	**Water**	**Electricity**	**Oxygen**	**Nitrogen**
1st Shift	2/10/21 7:00	125.000	0.980	0.950	1.510	299.000	0.900	0.090	13.000	16.000
	%	1.000	0.990	0.960	0.987	0.995	0.922	1.000	0.908	0.894
	2/10/21 8:00	105.000	0.990	0.990	1.520	300.000	0.920	0.110	14.000	17.000
	%	0.875	1.000	1.000	0.993	0.992	0.902	0.949	0.843	0.841
	2/10/21 9:00	105.000	0.990	0.990	1.520	300.000	0.920	0.110	14.000	17.000
	%	0.875	1.000	1.000	0.993	0.992	0.902	0.949	0.843	0.841
	2/10/21 10:00	105.000	0.990	0.990	1.520	300.000	0.920	0.110	14.000	17.000
	%	0.875	1.000	1.000	0.993	0.992	0.902	0.949	0.843	0.841
	2/10/21 11:00	105.000	0.990	0.990	1.520	300.000	0.920	0.110	14.000	17.000
	%	0.875	1.000	1.000	0.993	0.992	0.902	0.949	0.843	0.841
	2/10/21 12:00	110.000	0.990	0.950	1.520	300.000	0.920	0.110	14.000	17.000
	%	0.917	1.000	0.960	0.993	0.992	0.902	0.949	0.843	0.841
	10/2/21 13:00	105.000	0.990	0.990	1.520	300.000	0.920	0.110	14.000	17.000
	%	0.875	1.000	1.000	0.993	0.992	0.902	0.949	0.843	0.841
	10/2/21 14:00	105.000	0.990	0.990	1.520	300.000	0.920	0.110	14.000	17.000
	%	0.875	1.000	1.000	0.993	0.992	0.902	0.949	0.843	0.841

Table 4
Sample of the control chart calculated values

Shift	Hour	Date	TPP|H	Mean	LCL
1st Shift	7:00	2/10/21	1.00	0.87	0.69
	8:00	2/10/21	0.88	0.87	0.69
	…		…		…
	16:00	2/10/21	0.88	0.87	0.69
2nd Shift	17:00	2/10/21	0.88	0.87	0.69
	18:00	2/10/21	0.67	0.87	0.69
	…		…		…
	23:00	2/10/21	0.92	0.87	0.69
	24:00	2/10/21	0.88	0.87	0.69
3rd Shift	1:00	2/11/21	0.86	0.87	0.69
	…		…		…
	4:00	2/11/21	0.87	0.87	0.69
	5:00	2/11/21	0.92	0.87	0.69
	6:00	2/11/21	0.75	0.87	0.69

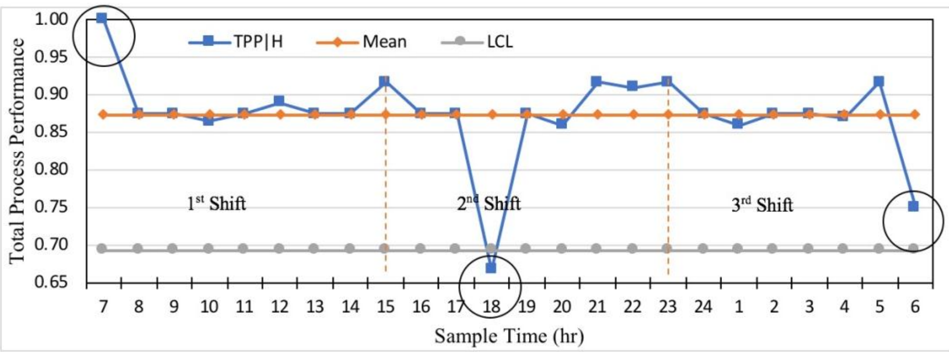

Fig. 11. $TPP|_H$ control chart

The control chart in Fig 12 shows an average value for $TPP|_H$ of %87.0, a minimum value of %67.0 at hour 18:00, and a maximum value of %100.0 at hour 7:00. The condition of the minimum value of $TPP|_H$ needs to be corrected as it is lower than the lower control limit (LCL) of %69.0. Also, the value of the sample at hour 6:00 seems too low, which affects the calculated value of the LCL. The value at 7:00 AM can also be considered an outlier. After removing the special causes of performance deficiency for the two lowest points, and removing the value at hour 7:00 as an outlier value, the control chart is reconstructed and now shows that all points are under control, and the LCL increased to %82.0, as shown in Fig 13. We can also set a target value of the LCL instead of calculating it as a process LCL, then improve the performance to meet the spec LCL.

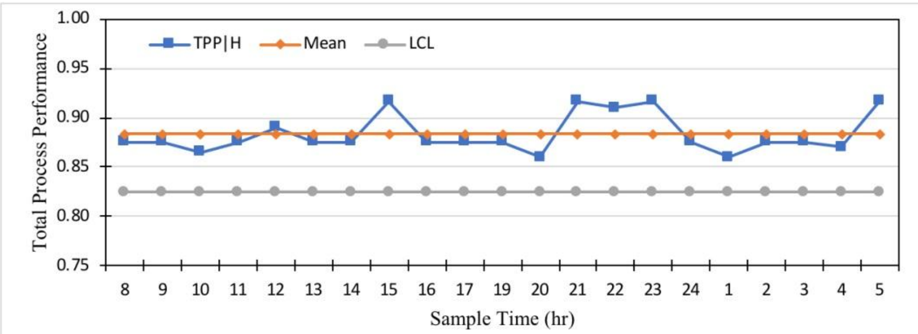

Fig. 12. $TPP|_H$ modified control chart

5. Results and Discussion

This section shows the results of the case study and focuses on how $TPP|_H$ could detect a performance deficiency and explains how the new performance indicator can track the process performance and help discover the root causes and set countermeasures. (Viveros, 2018). Table 4 shows the breakdown of the metrics used in calculating the performance value at 18:00, which was out of control.

Table 5
$TPP|_H$ metrics breakdown at 18:00 on 10/2/2021

Effectiveness				Efficiency					
Actual Values 10/2/21	Performance	Availability	Quality	Yield	Natural Gas	Water	Electricity	Oxygen	Nitrogen
18:00	80.000	0.990	0.990	1.520	300.000	0.920	0.130	14.000	17.000
Actual/Base	0.667	1.000	1.000	0.993	0.992	0.902	0.803	0.843	0.841

The $TPP|_H$ control chart showed a deficiency on 10/2/2021 at 18:00. The overall indicator breakdown investigation showed the following:

1. The production rate was too low.
2. The electricity power consumption was high, therefore, its efficiency was low.

The electric power consumption unit is kW.hr/ton, which is the consumed electric power per total production for one hour. Therefore, as the production amount per hour increases, the kWhr/ton decreases, and hence the process performance increases and vice versa. Fig 13 shows the electric power consumption during the day of the deficiency point.

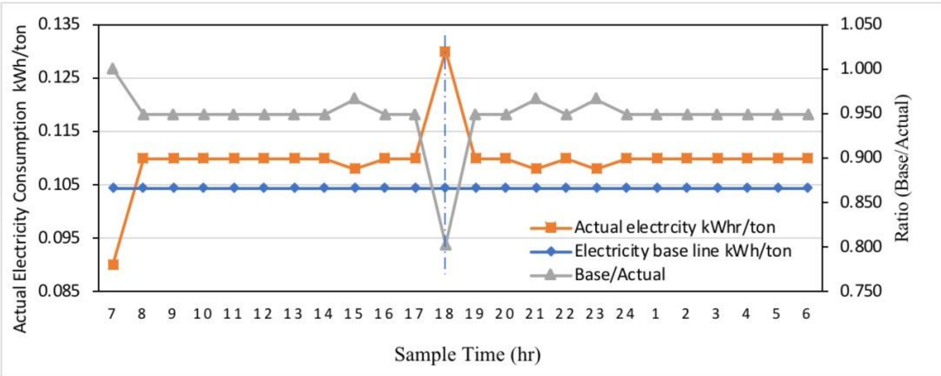

Fig. 13. The electric power consumption at the low-performance point

Fig 14 looks at the production output during the deficiency point, which showed that the main cause of deficiency was the decrease of the production rate at this time as a result of miss-operation (reasons like material flow problems, decrease furnace shaft discharge rate, a decrease of furnace shaft bed temperature, .etc.), which is a performance decline special cause.

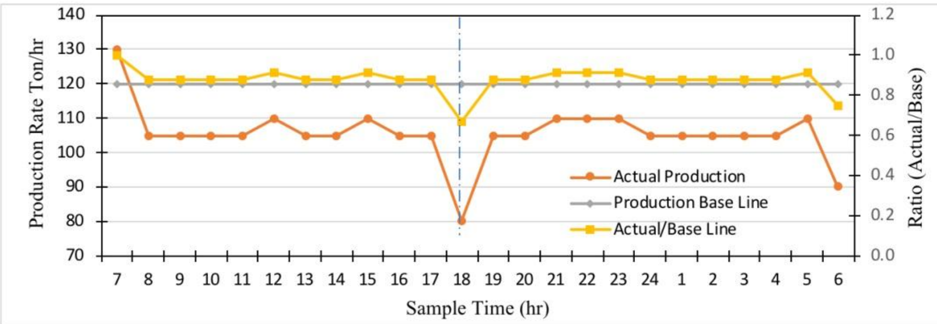

Fig. 14. Production performance at the low-performance point

The data breakdown and analysis showed that the operating crew in the first shift is more qualified than the other shifts' crews, which is shown as an increase in the average production rate during the 1st shift. Therefore, the $TPP|_H$ performance indicator proved that it is a proper tool for the evaluation of the process performance. It mimics the evaluation of the different working cells in an Amoeba management system. This system is used in case it is difficult to make each cell accountable for its actions independently (Urban, 2017). In the Amoeba management system, each cell has its complete accountability and undependability from other cells, which is difficult to attain. Thus the $TPP|_H$ indicator can facilitate the assessment of each Amoeba cell's performance and make each cell engaged in the Total Process Performance. This should contribute to decreasing the production cost per ton.

5.1. Comparing TPP/$_H$ with OEE and PEE

Fig 15 shows the comparison plots between the values of TPP|$_H$, OEE, and PEE. The TPP|$_H$, OEE, PEE, and the difference between the old indices (OEE and PEE) and the new index (TPP|$_H$) for 24 hours were calculated to make a comparison between these performance measurement indices. The results show that OEE and PEE are almost identical (superimposed in Fig 15) and higher than TPP|$_H$ values by about %4.5 on average. The difference between OEE, PEE, and TPP|$_H$ values depends mainly on the effect of the efficiency metrics values. Therefore, TPP|$_H$ is more sensitive than OEE and PEE to efficiency changes.

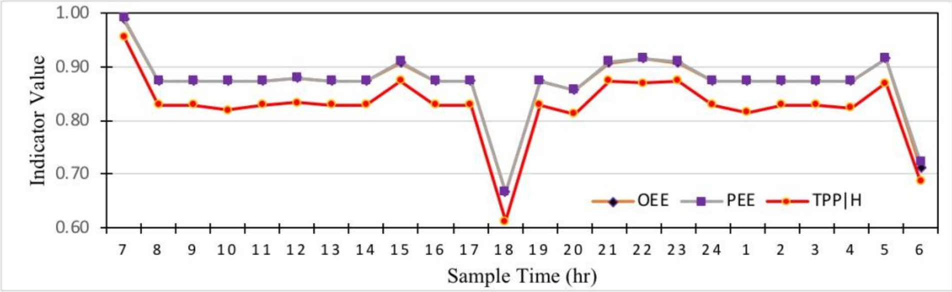

Fig. 15. Comparison between TPP|$_H$, OEE, and PEE

5.2. Software and user interface

Fig 16 shows the operator panel display window for the new Total Process Performance parameter TPP|$_H$ as part of the data collection and monitoring system developed software. The operator panel displays the chart of the TPP|$_H$, its control limit, and alarming conditions.

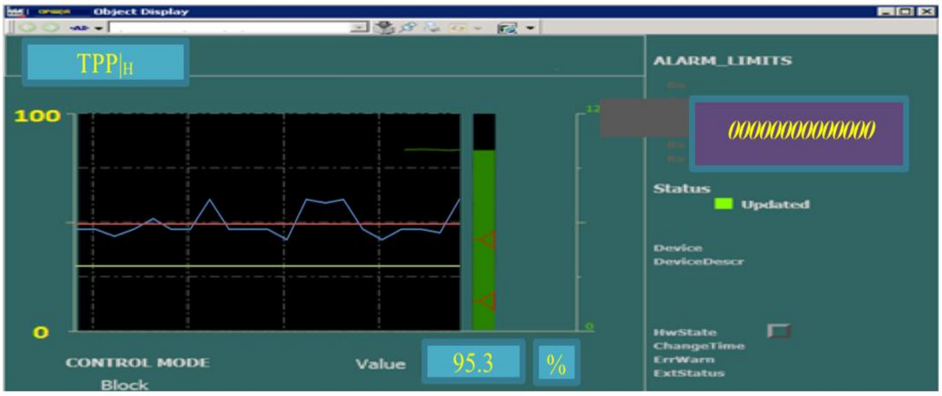

Fig 16. Operator panel display window for TPP|$_H$

Visualizing the pattern of the performance indicator in real-time through the use of the control charts allows for monitoring all of the operation parameters across the production section. This can be used as improvement guidance by following up on the declining operation parameters across the production section. This will help the floor managers to discover the root causes leading to low performance or high performance. Implementing the TPP|$_H$ showed an opportunity for improvement on the floor management level in case the indicator was applied.

6. Conclusions

Creating a single, more inclusive indicator for the Total Process Performance (TPP|$_H$) is very beneficial, especially for large organizations that include a large number of manufacturing processes. The developed indicator and the real-time monitoring system help discover any declining performance metric early, and enables deploying a quick action and thus avoiding the problem aggravation.

6.1. Future Work, Calculation of TPP/$_L$

The TPP|$_L$ should show the performance behavior due to internal and external factors that are in control by the top management which are out of the shop floor production system management scope. As TPP|$_L$ needs more data about the external factors and more data collection time, which was not available during the study, a future study to calculate the TPP|$_L$ for the direct reduction plant can be done and present the results on a control chart. A separate control chart should be made for each component in the

TPP|L to be able to analyze the final results and give information on the best-performing functions. It will also give insights about each indicator, leading to discovering the weak performing functions and which area of improvement is needed. It will give insights about the operating internal and external functions giving a chance to top management for intervention.

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