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METHODOLOGY OF OVERALL EQUIPMENT EFFECTIVENESS CALCULATION IN THE CONTEXT OF INDUSTRY 4.0 ENVIRONMENT

METODOLOGIA OBLICZANIA OGÓLNEJ EFEKTYWNOŚCI SPRZĘTU W KONTEKŚCIE ŚRODOWISKA INDUSTRY 4.0

Industry 4.0 and related Maintenance 4.0 demand higher requirement for productivity and maintenance effectiveness. Nakajim's OEE indicator still plays an important role in measuring effectiveness of production and maintenance. In connection with the current Industry 4.0 challenge, the issue of Industrial Internet of Things (IIoT) is highly accentuated. This topic includes the matter of autonomous management and communication of individual machines and equipment within higher and more complex production units. Authors propose original calculations OEE for the whole production line from OEE knowledge and individual machines, including knowledge of their nominal and actual performance. The presented solution allows a greater depth of analysis of machine efficiency and overall effectiveness calculation of different assembled production lines based on knowledge of individual machines efficiencies.

Keywords: *overall equipment effectiveness, availability, performance, quality, Industry 4.0.*

Industry 4.0 i związana z nią strategia Maintenance 4.0 stawiają wyższe wymagania odnośnie wydajności produkcji i utrzymania ruchu. Wskaźnik ogólnej efektywności urządzeń (OEE) Nakajimy nadal odgrywa ważną rolę w pomiarach efektywności produkcji i utrzymania ruchu. W związku z wyzwaniami stawianymi obecnie przez Industry 4.0, dużą uwagę zwraca się na koncepcję Przemysłowego Internetu Rzeczy. Obejmuje ona kwestię autonomicznego zarządzania i komunikacji pomiędzy poszczególnymi maszynami i urządzeniami w bardziej złożonych jednostkach produkcyjnych wyższego stopnia. Autorzy niniejszej pracy proponują oryginalną metodę obliczania OEE dla całej linii produkcyjnej na podstawie znajomości ogólnej efektywności urządzeń oraz efektywności pojedynczych maszyn, w tym wiedzy o ich nominalnej i rzeczywistej wydajności. Przedstawione rozwiązanie pozwala na głębszą analizę wydajności maszyn oraz obliczanie ogólnej efektywności różnych linii produkcyjnych w oparciu o wiedzę na temat wydajności poszczególnych maszyn.

Słowa kluczowe: *ogólna efektywność sprzętu, gotowość, wydajność, jakość, Industry 4.0.*

1. Introduction

Production line is generally a system composed of numbers of production equipment. In order to achieve proper competitiveness of production it is necessary to monitor and evaluate several operational parameters. One of these parameters is effectiveness. Measuring the effectiveness of production machines (including production lines) is one of the important factors of economy of operation [11, 24].

Generally, there are several indicators for numerical representation of effectiveness in the manufacturing organization [8].

These indicators are one of the key performance indicators KPIs. Key performance indicators are a set of standards focused on aspects that critically affect the present or the future success of organization [14].

Nakajima [21] came with the proposal to measure the performance of operational management and maintenance in his concept Total Productive Maintenance (*TPM*). He needed to measure the effectiveness of the proposed managerial maintenance measures in some way, which he succeeded in proposing the Overall Equipment Effectiveness (*OEE*) indicator. The specificity of this indicator was that preventive maintenance periods were off-set by the *OEE* indicator to the so-called Total Effective Equipment Productivity (*TEEP*) indicator. It is understandable that enormous requirements for the duration of preventive maintenance also reduce the possibility of using the production equipment and therefore preventive maintenance should also be included in downtime due to maintenance.

Drożyner and Mikolajczak [8] used *OEE* indicator with somewhat changed terminology and together with Paret's analyse evaluation of efficiencies of the production equipment.

Hartmann [12] discusses the *OEE* structure in detail, but does not associate indicator with economics of operation of production equipment, even does not describe a deeper structure of indicators.

Puvanasvaran [25] intend to examine and quantify the hidden lean waste in *OEE* from the perspective of method and work of an operation with the integration of Maynard's Operation Sequence Technique (*MOST*) study. Operations are analysed in every single step and broken down into details of activities, which are then re-designed for minimal non-value added activity in operation based on the standard allowable. The *OEE* data after the study of work is computed and compared with the *OEE* before the MOST study. The comparison shows the improvement in term of *OEE* after the MOST study and this implies that the hidden waste inside *OEE* definition could be tracked down for a better effectiveness.

Coit [5] describes the use of a GA (Genetic Algorithm) to solve the redundancy allocation problem for a series-parallel system. In this problem formulation, there is a specified number of subsystems and, for each subsystem, there are multiple component choices which can be selected (assuming an unlimited supply of each), and used in parallel.

Antosz [3] shows that data obtained from measurement of particular indicators are a primary source of information on the necessity of taking particular actions. Large companies are particularly willing to implement appropriate indicators of effectiveness evaluation because of a large number of machines and a vast range of their technical maintenance. Indicator which is importance in the production process improvement is *OEE* indicator. *OEE* describes the three basic areas of business activity as availability, efficiency and quality of products. Calculating *OEE* enables to define the improvement actions implemented in the field of production processes, it allows to measure their effect on the implementation and the elimination of existing problems. It allows to identify bottlenecks and main problems of a company.

In practice, two approaches may be used. Among the indicators recommended by the standard there are *MTBF* (Mean Time Between Failure) and *MTTR* (Mean Time To Restoration) indicators. *MTBF* (Mean Time Between Failure) shows from a static point of view how often the technical object is damaged. In enterprises this indicator is used to determine the preventive maintenance schedule. *MTTR* (Mean Time To Restoration) defines the average time required to repair at the moment of failure. It is used to evaluate the effectiveness of staff maintenance services, as well as to assess repair tasks they carry out [10, 17].

Ding [7] in their article describe a novel and effective system reliability evaluation method in terms of failure losses for manufacturing systems of job shop type, and then the failure losses based component importance measure (*CIM*) is used for importance analysis of equipment.

Kuo [13, 27, 16] provide a vague global reliability evaluation for manufacturing system that is also helpless for targeted improving effort, and criticality assessment based on importance measures is more meaningful and intuitive for the prioritization of reliability improvements or maintenance activities. The main idea lies in the fact that some components have more significance during manufacturing processes than others.

System reliability is effectively evaluated by the proposed failure losses based method. In contrast, the traditional *MTBF* or *MTTR* based method is applicable to individual equipment. *FT total* (Total failure times) and *FL total* (Total failure losses) are novel and efficient reliability measures for job shop manufacturing system, and it is hard and improper to apply system *MTBF* to quantify the system reliability owing to the system attributes of multiple failure modes and multiple failure states. [7]

The effective throughput, or the net throughput, also called *OEE* that is the number of conforming parts produced by the system in a given time. Grounding on this background knowledge, the production quality paradigm can be formulated in the following terms: Production quality is the discipline that combines quality, production logistics, and maintenance methods and tools to maintain the throughput and the service level of conforming parts under control and to improve them over time, with minimal waste of resources and materials [6, 15, 23].

In his paper, Reyes [26] provides background of *OEE* and explores its limitation. The paper also shows conceptual and mathematical development of *ORE* measurement and formulas for calculation. Empirical and simulation-based investigations and applications of *ORE* are carried out through two case studies for validation. The consideration in the *ORE* approach of process cost variations, material cost variations and material efficiency may be able to make the overall effectiveness measure, on certain process, more complete and achievable than the measure obtained from the traditional *OEE*.

In an example of scope extension, Al-Najjar [1] presented overall process effectiveness (*OPE*) as a measure of all losses associated with an entire process. He also recognised that machines of the same type may have dissimilar OPE values. Scott [28] also statement that gains in overall equipment effectiveness (OEE), while important and on-going, are insufficient, because no machine is isolated. Materials and processes must be successfully choreographed among hundreds of tools to achieve Overall Factory Effectiveness (OFE). The ultimate objective is a highly efficient integrated system, not brilliant individual tools. However, successful analysis on OEE only is not sufficient as no machine is isolated in a factory, but operates in a linked and complex environment. A wider approach has to focus also on the performance of the whole factory. [22]

Nachiappan [20] aims to present an approach to measure the overall line effectiveness (*OLE*) in continuous line-manufacturing system. an *OLE* value, calculated for one product line, can be used to compare line performance across the factory there by highlighting any poor product (loss-making product) being manufactured in the organization.

Muthiah [19] presented on *OEE*'s inadequacy at the factory level and proposed overall throughput effectiveness (*OTE*). It measures factory-level performance and can also be used for performing factory-level diagnostics such as bottleneck detection and identifying hidden capacity.

Braglia [4] showed new efficiency metric, which is called (*OEEML)* and applied to an industrial case, concerning an automated line for engine basements manufacturing.

In TQMain is measured by a modified version of the overall equipment effectiveness (*OEE*) measure of *TPM*, which he calls overall process effectiveness (*OPE*). The *OEE* measure combines the six big losses of *TPM* under three headings: availability (including preventive down time), speed (actual production rate/theoretical production rate) and quality. [29]

OEE is useful tool to highlight potential areas of improvement because it is quantitative measurement of *TPM*. Continuous improvement of *OEE* requires labour to top management engagement in betterment of equipment and plant to obtain fruitful benefits [30].

While the results for *OEE* by ignoring a considerable amount of possible hidden losses might be satisfying, the *OEE-MB* report shows potential room for improvement. It reflects changes in both the internal and external market for the steel industry, and therefore provides a tool not only for monitoring but also for managing improvement [31].

In particular, we have shown how the 5-whys analysis can be actually used to eliminate the *OEE*'s speed loss. The 5-whys analysis technique has been proven to be an effective approach to tackle speed loss, a loss which has been regarded as the most dominating loss among all types of *OEE* losses and one which is difficult to eliminate. Although the 5-whys analysis was originally designed to reduce quality loss, set up and changeover time loss, we have shown evidence that the use of 5-whys analysis can be extended to other areas of the six big losses of *OEE*, namely speed loss [18].

Measurement is an important requirement of continuous improvement process. It is necessary to establish appropriate metrics for measurement purposes. From generic perspective, *TPM* can be defined in terms of Overall Equipment Effectiveness (*OEE*) which in turn can be considered a combination of the operation maintenance, equipment management and available resources. The goal of TPM is to maximise equipment effectiveness, and the *OEE* is used as a measure [32].

An *OEE* score obviously requires proper interpretation. The detection of critical points in production lines and taking measures to increase the reliability of the individual machines is what *OEE* is calculated for. The relationship between FMEA and *OEE* requires that indices of operational reliability of the investigated production line be calculated. The impact of the individual units comprising the production line on its failure rate can be assessed on the basis of the number of failures and downtimes of these units. Indicators of reliability can be used to pin down weak links in the system [11].

Duran [9] proposes new index for a comprehensive and systematic measurement of sustainability and throughput performance in production systems. The proposed index, called Sustainable Overall Throughput Effectiveness (*S.O.T.E.*), is designed on the basis of a comparison of the environmental and operational factors. Specifically, it integrates the following four dimensions: availability, utilization, performance, and environmental sustainability. The way each dimension is measured is explained and justified. This index uses the overall environmental equipment effectiveness (*OEEE*) index, which is based on the Overall Equipment Effectiveness (*OEE*) index.

Currently applied Industry 4.0 concept is based on decentralization of individual machines in manufacturing process. Authors' proposed methodology focused on calculation of *OEE* for serial, parallel and combined settings of production lines when data are gathered via sensors. Particular attention is paid to serial settings of production lines which are more widespread in the industry. Main advantage of presented solution allows a greater depth of analysis of machine efficiencies.

2. Materials and methods

Before actual determination of effectiveness indicators, it is necessary to define time of losses that may potentially occur during total available time. Generally, there are these times losses:

- **Non-scheduled time t_{non}** – all time the production line is not being used.
- - **Organizational downtime t_{org}** - production line downtime due to organizational causes (time for personal relaxation, lack of staff…).
- **Logistic downtime t_{log}** – machine downtime due to logistical reasons (lack of material, material damage, incorrect order, lead time, warehouse, insufficient stock, etc.).
- **Preventive maintenance downtime t_{pre}** – production line downtime due to preventive maintenance, which cannot be done during operation [10].
- **Setup and adjustment downtime t_{set}** – production line downtime due to necessary setup and adjustment (e.g. replacement of worn tools).
- **Corrective (functional and minor) maintenance downtime t_{cor}** – production line downtime due to failures and caused of other dependent losses (greater extent of damage, safety hazards, adverse environmental impacts) including minor failures (e.g. product blocked in the machine).
- **Loss time due to reduced performance efficiency t_{per}** – time loss due to lower performance due to worsen technical state (loss adjustment, wear, corrosion, deformation, cracks, etc.).
- **Loss time due to production of non-conforming products t_{pro}** – there are generally two categories of non-conforming product origin:
  a) as a result of defective manufacturing process, which is caused by a poor monitoring, improperly performed maintenance (repair), and adjusting the parameters influencing the capability of production line,
  b) due to unstable state of production process at the start of production. [2]

For a calculation of effectiveness indicators it is necessary to begin with definition of total available time. Total available time can be defined as the calendar time, which can be potentially used for production, for example, 8,760 h per year, 24 hours per day, etc. Available time may be (in limiting case) equal to the net operating time, in the event that there are no time losses and production line is required continuously. This situation is almost impossible in real operation because work shift usually consists (besides net operating time) of a number of time losses and downtimes. [2]

Various operational or production times are calculated by subtracting the time of loss from total available (calendar) time as it is shown in Table 1. Calculated operational and production times are used to construct the coefficients, which are used for calculation of effectiveness indicators. [2]

Figure 1 describes the breakdown of the net available time the individual operating and production times and each time losses that can occur during operation. [2]

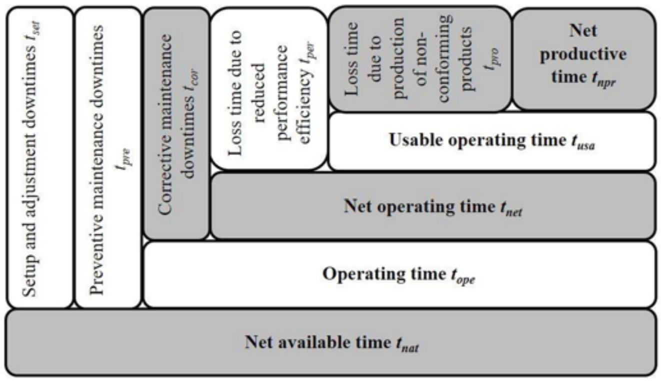

Fig. 1. Net available time breakdown [2]

Coefficients for calculation of effectiveness indicators of production line are calculated by operating and production times in different ratios. It is possible to define these coefficients:

- ***Coefficient of preventive Maintenance downtimes, setup and adjustment downtimes M*** – this coefficient is calculated as op-

Table 1. Calculations of operational and production times [2]

Type of time	Calculation (verbally)	Calculation
Net available time t_{nat}	Total available time t_{ava} – Non-scheduled time t_{non} – Organizational downtimes t_{org} – Logistic downtimes t_{log}	$t_{nat} = t_{ava} - t_{non} - t_{org} - t_{log}$
Operating time t_{ope}	Net available time t_{nat} – Preventive maintenance downtimes t_{pre} – Setup and adjustment downtimes t_{set}	$t_{ope} = t_{nat} - t_{pre} - t_{set}$
Net operating time t_{net}	Operating time t_{ope} – Corrective maintenance downtimes t_{cor}	$t_{net} = t_{ope} - t_{cor}$
Usable operating time t_{usa}	Net operating time t_{net} – Loss time due to reduced performance efficiency t_{per}	$t_{usa} = t_{net} - t_{per}$
Net productive time t_{npr}	Usable operating time t_{usa} – Loss time due to production of non-conforming products t_{pro}	$t_{npr} = t_{usa} - t_{pro}$

erating time divided by running time without organizational and logistical downtimes (1):

$$M = \frac{t_{ope}}{t_{nat}} = \frac{t_{ava} - t_{non} - t_{org} - t_{log} - t_{pre} - t_{set}}{t_{ava} - t_{non} - t_{org} - t_{log}} \tag{1}$$

– ***Coefficient of Failures F*** *(breakdowns)* – this coefficient is calculated as net operating time divided by operating time (2):

$$F = \frac{t_{net}}{t_{ope}} = \frac{t_{ava} - t_{non} - t_{org} - t_{log} - t_{pre} - t_{set} - t_{cor}}{t_{ava} - t_{non} - t_{org} - t_{log} - t_{pre} - t_{set}} \tag{2}$$

– ***Coefficient of Availability A*** – this coefficient is calculated as coefficient of preventive maintenance downtimes, setup and adjustment downtimes M multiplied by coefficient of failures F (3) [2]:

$$A = M \times F = \frac{t_{net}}{t_{nat}} \tag{3}$$

– ***Coefficient of Performance P*** – actually, there are two possibilities how to calculate this coefficient. Using production times it is necessary to calculate usable time divided by net operating time (4) [2]:

$$P = \frac{t_{usa}}{t_{net}} = \frac{t_{ava} - t_{non} - t_{org} - t_{log} - t_{pre} - t_{set} - t_{cor} - t_{per}}{t_{ava} - t_{non} - t_{org} - t_{log} - t_{pre} - t_{set} - t_{cor}} \tag{4}$$

The second option is to use the ratio between real and nominal performance for the calculation (5):

$$P = \frac{P_{rea}}{P_{nom}} \tag{5}$$

where: P_{nom} – Nominal performance (units)
P_{rea} – Real performance (units)

– ***Coefficient of Quality Q*** – as well as when calculating the performance coefficient, it is possible to calculate the quality coefficient in two ways Using production times it is necessary to calculate net productive time divided by usable time (6) [2]:

$$Q = \frac{t_{npr}}{t_{usa}} = \frac{t_{ava} - t_{non} - t_{org} - t_{log} - t_{pre} - t_{set} - t_{cor} - t_{per} - t_{pro}}{t_{ava} - t_{non} - t_{org} - t_{log} - t_{pre} - t_{set} - t_{cor} - t_{per}} \tag{6}$$

The second option is to use the ratio between the manufactured products and the total number of products produced (7):

$$Q = \frac{u_{con}}{u_{con} + u_{non}} \tag{7}$$

where: u_{con} – Number of conforming units
u_{non} – Number of non-conforming units

Overall Equipment Effectiveness OEE indicator of production line can be calculated by coefficients of availability, performance and quality. Calculation of Overall Equipment Effectiveness OEE indicator shows equation (8):

$$OEE = \frac{t_{npr}}{t_{nat}} = A \times P \times Q \tag{8}$$

Within Industry 4.0, individual machines are autonomous and communicate with each other. Industrial Internet of things (IIoT) allows to collect a large amount of data that can be further processed and used in a variety of areas such as logistics, energy consumption, meteorology, and, of course, production (maintenance) efficiency. A new production approach based on decentralization, where data is collected locally and subsequently processed, brings a number of benefits to optimize the production process. The main idea presented by the authors is how to determine the overall integral indicators of production efficiency from the partial data of the monitored machines.

3. Calculation of *OEE* indicator in a serial, parallel and combined machine systems in the production line

Authors assume that the system consists of n individual machines and they create a production line with serial, parallel or combined system. Furthermore, assume that OEE_i of individual machines is known. Furthermore, nominal performance $Pnom_i$, real performance of individual machines $Prea_i$ and number of conforming units u_{con} are known. The task is to calculate *OEE* for whole production line with serial, parallel or combined system.

3.1. Calculation of *OEE* for serial system

In order to determine the OEE of a production line with serial system, it is necessary to calculate with individual coefficients of the efficiency indicator of individual machines (equipment). As mentioned above, it is the A_i coefficient, the P_i coefficient and the Q_i coefficient. In order to determine the *OEE* of a production line with individual machines in series, it is necessary to calculate "per partes" of the resulting values of the individual coefficients (A_s, P_s, Q_s), which they enter the calculation of the *OEE's* of the whole production line.

Calculation of availability of production line A_s

In order to determine the influence on coefficient of availability A even on overall availability of production line is necessary to know, that each machine can take different states during operational time. These states can be measured by periods (time) – production time t_{pro}, setup and adjustment time t_{set}, maintenance after failure time t_{intx} (including both maintenance after failure till 5 minutes t_{int0} and over 5 minutes t_{int5}), preventive maintenance time t_{pre}, It is desirable for the machine to work, i.e. machine was not in the downtime - outside the production time t_{pro}. For example, if the production line is created by two machines, than it is necessary to know the size of individual times in which machines were during operational time for calculation of availability coefficient. Intersections (time overlap) of downtime are important to determine, i.e. time outside of the production time when the two machines do not produce. Overall downtime intersection rate of both machines can be termed as the downtime intersection time $t_{int1,2}$. This reflects the relation for the calculation of overall availability for n machines (9). This relation is based on the principle of inclusion and exclusion in number of probability, more specifically, the positive parts of these numbers.

Relation for the calculation of coefficient of availability for n machines with serial system formulated as follow:

$$\begin{aligned} A_{1,2,\dots,n_s} &= \left(\sum_{k=1}^{n} \frac{t_{net_k}}{t_{nat}} + \sum_{\alpha;|\alpha|=2} \frac{t_{int\alpha}}{t_{nat}} - \sum_{\alpha;|\alpha|=3} \frac{t_{int\alpha}}{t_{nat}} + \dots + (-1)^{n-1} \sum_{\alpha;|\alpha|=n-1} \frac{t_{int\alpha}}{t_{nat}} + (-1)^n \frac{t_{int(1,2,\dots,n)}}{t_{nat}} - n + 1\right)^+ \\ &= \left(\sum_{k=1}^{n} A_k + \sum_{\alpha;|\alpha|=2} \frac{t_{int\alpha}}{t_{nat}} - \sum_{\alpha;|\alpha|=3} \frac{t_{int\alpha}}{t_{nat}} + \dots + (-1)^{n-1} \sum_{\alpha;|\alpha|=n-1} \frac{t_{int\alpha}}{t_{nat}} + (-1)^n \frac{t_{int(1,2,\dots,n)}}{t_{nat}} - n + 1\right)^+ \end{aligned} \tag{9}$$

– in the above, series are summed over all multindexes of lengths 2, 3,..., n -1, ie. over all the pairs $\alpha = (k_1, k_2)$, where $1 \le k_1 < k_2 \le n$

triplets $\alpha = (k_1, k_2, k_3)$, where $1 \le k_1 < k_2 < k_3 \le n$, ..., and

$(n - 1)$ tuples $\alpha = (k_1, k_2,...,k_{n-1})$, where $1 \le k_1 < k_2 < ... < k_{n-1} \le n$.

The Influence of machine performance coefficient on production line overall performance

Overall performance of production line will not ever be greater than machine performance, which has in production line the lowest nominal performance $Pnom_i$. In order to calculate performance coefficient, it is necessary to know real performance Pr_i of individual machines. The coefficient of production line performance is calculated as fraction of lowest real performance $Prea_i$ from all machines with the lowest rated performance $Pnom_i$ from all machines (10). Relation for calculation of coefficient of performance for n machines with serial system formulated as follow:

$$P_{1,2,\ldots,ns} = \frac{min\left(P_{rea_1};P_{rea_2};\ldots;P_{rea_n}\right)}{min\left(P_{nom_1};P_{nom_2};\ldots;P_{nom_n}\right)} \quad (10)$$

where: P_{nom} – Nominal performance (units)
P_{rea} – Real performance (units)

The Influence of machine quality coefficient on the overall production quality of production line

It is less demanding to determine coefficient of quality Q for the all systems, when product of coefficients of quality Q_i of individual machines is used (11). Relation for calculation of quality for n machines in serial system formulated as follow:

$$Q_{1,2,\ldots ns} = \prod_{i=1}^{n} \frac{u_{con} + \sum_{k=i+1}^{n} u_{non_i}}{u_{con} + u_{non_i} + \sum_{k=i+1}^{n} u_{non_i}} = \prod_{i=1}^{n} Q_i \quad (11)$$

where: u_{con} – Number of conforming units
u_{non} – Number of non-conforming units

Determination of OEE for serial system

Determination of overall equipment effectiveness with serial system has to respect the rules for calculation of coefficient of availability, coefficient of performance and coefficient of quality (12). Relation for the calculation of the *OEE* for n machines with serial system formulated as follow:

An example of calculation of the overall equipment effectiveness

An example illustrating values of input data of whole production line (representing three equipment - Figure 2) shown in this part of paper to better understand the methodology used to calculate the overall equipment effectiveness. Table 2 shows illustrative input data of concerning downtimes (Figure 3), performance, conforming and non-conforming units. In other words, there are individual input data for three specific equipment that form a whole production line.

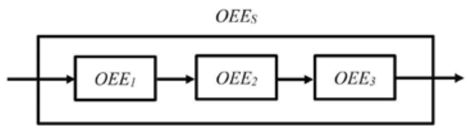

Fig. 2. Production line represented three equipment in serial system

Table 2. Partial data concerning downtimes, performance, conforming and non-conforming units of each equipment

Monitored parameter	Equipment 1	Equipment 2	Equipment 3
Running time without organizational and logistic downtimes t_{orl}		24 h	
Preventive maintenance downtime t_{pre}	0,5 h	0,5 h	0,5 h
Setup and adjustment downtime t_{set}	0,5 h	0,0 h	0,0 h
Corrective maintenance downtime t_{cor}	0,0 h	0,5 h	1,5 h
Downtimes total	1,0 h	1,0 h	2,0 h
Interception of downtimes with Equipment 1	x	x	x
Interception of downtimes with Equipment 2	0,5 h	x	x
Interception of downtimes with Equipment 3	0,5 h	1,0 h	x
Overall interception of downtimes		0,5 h	
Nominal performance	2300 units	2300 units	2200 units
Real performance	2250 units	2200 units	2100 units
Non-conforming units	10 units	20 units	30 units

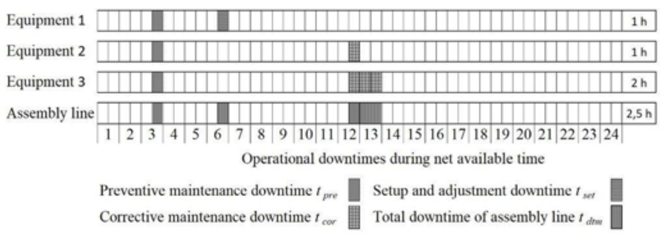

Fig. 3. Production line – downtime breakdown

The following is the calculation of the individual coefficients (A, P, Q) for specific equipment from the partial data:

$$OEE_{1,2,\ldots,n_s} = \left(\sum_{k=1}^{n} A_k + \sum_{\alpha;|\alpha|=2} \frac{t_{int\alpha}}{t_{nat}} - \sum_{\alpha;|\alpha|=3} \frac{t_{int\alpha}}{t_{nat}} + \ldots + (-1)^{n-1} \sum_{\alpha;|\alpha|=n-1} \frac{t_{int\alpha}}{t_{nat}} + (-1)^n \frac{t_{int(1,2,\ldots,n)}}{t_{nat}} - n + 1\right)^{+}$$
$$\times \frac{\min\left(P_{rea_1};P_{rea_2};\ldots;P_{rea_n}\right)}{\min\left(P_{nom_1};P_{nom_2};\ldots;P_{nom_n}\right)} \times \prod_{i=1}^{n} Q_i \quad (12)$$

$$A_{1,2,3s} = \frac{t_{nat} - t_{dtm_1}}{t_{nat}} + \frac{t_{nat} - t_{dtm_2}}{t_{nat}} + \frac{t_{nat} - t_{dtm_3}}{t_{nat}} + \frac{t_{int1,2}}{t_{nat}} + \frac{t_{int1,3}}{t_{nat}} + \frac{t_{int2,3}}{t_{nat}} - \frac{t_{int1,2,3}}{t_{nat}} - 2 = \frac{24-1}{24} + \frac{24-1}{24} + \frac{24-2}{24} + \frac{0,5}{24} + \frac{0,5}{24} + \frac{1}{24} - \frac{0,5}{24} - 2 = 0,8958 \quad (13)$$

$$P_{1,2,3s} = \frac{min\left(P_{rea_1}; P_{rea_2}; P_{rea_3}\right)}{min\left(P_{nom_1}; P_{nom_2}; P_{nom_3}\right)} = \frac{min(2250; 2200; 2100)}{min(2300; 2300; 2200)} = 0,9545 \quad (14)$$

$$Q_{1,2,3s} = \frac{u_{con} + u_{non_2} + u_{non_3}}{u_{con} + u_{non_1} + u_{non_2} + u_{non_3}} \times \frac{u_{con} + u_{non_3}}{u_{con} + u_{non_2} + u_{non_3}} \times \frac{u_{con}}{u_{con} + u_{non_3}} = \frac{2400+20+30}{2400+10+20+30} \times \frac{2400+30}{2400+20+30} \times \frac{2400}{2400+30} = 0,9714 \quad (15)$$

$$OEE_{1,2,3s} = A_{1,2,3s} \times P_{1,2,3s} \times Q_{1,2,3s} = 0,8958 \times 0,9545 \times 0,9714 = 0,8307 \quad (16)$$

The results of the calculations (13) – (16) are clearly recorded in table 3. The results show that the calculated aggregate values from the partial input data are equal with the results for the whole production line (Table 3 and Figure 4).

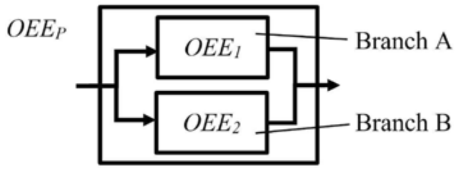

Fig. 5. Production line represented parallel system

Table 3. Results of overall effectiveness equipment calculation

Equipment 1	Equipment 2	Equipment 3	Equipment 1,2,3 s	Production line
$A_{1s} = 0,958$	$A_{2s} = 0,958$	$A_{3s} = 0,917$	$A_{1,2,3s} = 0,8958$	$A_s = 0,8958$
$P_{1s} = 0,978$	$P_{2s} = 0,957$	$P_{3s} = 0,955$	$P_{1,2,3s} = 0,9545$	$P_s = 0,9545$
$Q_{1s} = 0,995$	$Q_{2s} = 0,990$	$Q_{3s} = 0,986$	$Q_{1,2,3s} = 0,9714$	$Q_s = 0,9714$
$OEE_{1s} = 0,9330$	$OEE_{2s} = 0,9079$	$OEE_{3s} = 0,8623$	$OEE_{1,2,3s} = 0,8307$	$OEE_s = 0,8307$

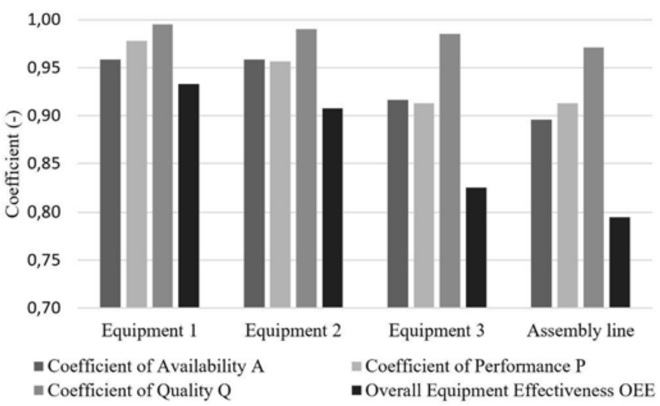

Fig. 4. Results of OEE calculation for serial system

3.2. Calculation of *OEE* for parallel system

Determination of interdependence of machines with parallel system as one production unit is based on relation for calculation of weighted average. For calculation of OEE_p (parallel system – Figure 5) applies (17) (weighted average), which takes individual *OEE* of machines and their performance P_{nom} rate. The relation is independent of the different values of individual performance of machines and overlapping loss times. All machines of production line with parallel system must be substitutes (they must produce the same products) and independent of each other.

$$OEE_{1,2,\&,np} = \frac{(OEE_1 \times P_{nom_1} + OEE_2 \times P_{nom_2} + \ldots + OEE_n \times P_{nom_n}}{P_{nom_1} + P_{nom_2} + \ldots + P_{nom_n}} = \frac{\sum_{i=1}^{n} OEE_i \times P_{nom_i}}{\sum_{i=1}^{n} P_{nom_i}} \quad (17)$$

Example of calculation the overall equipment effectiveness

Example with illustrative values of input data of whole production line (represented by two parallel branches) is shown in Table 4. Table 4 consists of nominal performance P_{nom} and previously calculated *OEE* of each branch. Calculation of *OEE* is realised by equation (18).

$$OEE_{1,2p} = \frac{OEE_1 \times P_{nom_1} + OEE_2 \times P_{nom_2}}{P_{nom_1} + P_{nom_2}} = \frac{0,8 \times 2200 + 0,9 \times 2100}{2200 + 2100} = 0,8488$$

Table 4. Illustrative values of input data of whole production line

	Nominal performance P_{nom}	OEE_n
Branch A	2200 units	0,800
Branch B	2100 units	0,900
Production line		0,8488

(18)

3.3. Calculation of *OEE* for combined system

Combined system is a mixed system of (machines) elements. It is a combination of serial and parallel system – Figure 6. In the case of combined system is calculated as a whole system according to equation (22).

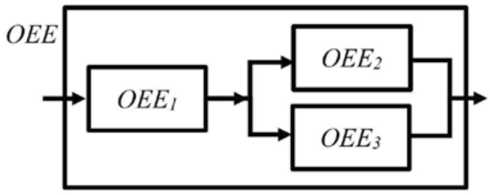

Fig. 6. Production line represented combined system

Table 5. Input data concerning downtimes, performance, conforming and non-conforming units of whole production line

Net available time t_{nat}	24 h
Total downtime of production line $t_{dtm} = t_{set} + t_{pre} + t_{cor}$	3 h
Nominal performance P_{nom}	2500 units
Real performance P_{rea}	2000 units
Non-conforming units u_{non}	100 units
Conforming units u_{con}	1900 units

Example of calculation the overall equipment effectiveness

Example with illustrative values of input data of whole production line shown in Table 5 shows illustrative input data of concerning downtimes, performance, conforming and non-conforming units.

The input data from Table 3 can be used to calculate the individual partial coefficients. Subsequently from these partial coefficients OEE indicator is calculated:

$$A = \frac{t_{nat} - t_{dtm}}{t_{nat}} = \frac{25-3}{25} = 0{,}875 \tag{19}$$

$$P = \frac{P_{rea}}{P_{nom}} = \frac{2000}{2500} = 0{,}800 \tag{20}$$

$$Q = \frac{u_{non}}{P_{rea}} = \frac{1900}{2000} = 0{,}950 \tag{21}$$

$$OEE = A \times P \times Q = 0{,}875 \times 0{,}800 \times 0{,}950 = 0{,}6650 \tag{22}$$

The results of the calculations (19) – (22) are clearly shown in Table 6.

Table 6. Results of overall effectiveness equipment calculation for whole production line

Coefficient of Availability A	0,875
Coefficient of Performance P	0,800
Coefficient of Quality Q	0,950
Overall Equipment Effectiveness OEE	0,6650

4. Conclusion

Proposed approach complies with currently applied Industry 4.0 concept, when effectiveness indicators are implemented into key maintenance performance indicators, which allows real-time processing of collected information from the manufacturing process and subsequently automatically evaluates its effectiveness on local and global level. Proposed methodology identifies weaknesses in the manufacturing process, which may be eliminated by corrective measures.

Authors proposed original *OEE* calculations for mainly serial production lines from the knowledge of *A, P, Q* of individual machines. Main advantage of presented solution allows a greater depth of machines efficiency analysis which fulfils with approach of production based on decentralization.

It is relevant to point out the disadvantages of effectiveness indicators, consisting in the fact that they do not take into account other relevant factors (e.g. operating costs, value of inventories of spare parts, the productivity of the manufacturing process, age of production equipment, etc.) and that there is a problem with finding all the necessary input data in order to calculate *OEE*.

Effort to achieve 100 % values of indicators leads to disproportionate growth of operational and maintenance costs. Approach of top management of organization and maintenance management must be activated when the indicators become stagnant or declining.

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