Economic Research, Vol. 25 (2012) No. 4 (1033-1050)

OVERALL COST EFFICIENCY

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Considering the present state of the art among the production optimization frameworks, the Overall Equipment Efficiency methodology is the most popular one. However, this methodology approaches production optimization only from the technology point of view and ignore the economic perspective of optimization. This is why we developed a new key performance indicator Overall Cost Efficiency aimed at measuring the cost efficiency of a production process in real time. Its application is based on the Overall Equipment Efficiency measurements and is convenient for application in industrial management praxis. We have used an ordinary mathematical modelling approach combined with descriptive microeconomic analysis techniques

Keywords:

- technical efficiency
- cost efficiency
- productivity
- microeconomics
- industrial management

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I. INTRODUCTION

Production optimization is one of research fields that lies at the cross-section of a microeconomics, mathematics and informatics. One of the special research issues includes the so-called Real Time Production Optimization models (RTPO models). Their goal is to improve the efficiency and predictability of the optimization methodology itself, and to improve the flexibility in terms of the types of proxy models that can be used.The natural background for development of the RTPO models is provided by the mathematical optimization techniques (see Strasek, 2003). Considering the present state of the art among the production optimization frameworks, the Overall Equipment Efficiency (OEE) methodology is the most popular one. However, this and other RTPO methodologies approach production optimization only from the technology point of view and ignore the economic perspective of the optimization.

The present paper introduces a new key performance indicator (KPI) aimed at bridging this gap. Our KPI measures not only the technical efficiency of production, but also the belonging cost efficiency in real time. Especially from the industrial management and from the productivity management point of view, it is crucial to know by what percentage the actual costs are higher due to the reduction of technical efficiency. For this purpose we suggest the use of Overall Cost Efficiency (OCE) framework. Its theoretical deduction is the basic issue of the article which is organized as follows. In chapter two the Overall Equipment Efficiency (OEE) framework is reviewed. In chapter three the microeconomic relationships between productivity and production costs are described. Chapter four develops an Overall Cost Efficiency (OCE) framework, and chapter five concludes with an industrial management point of view on the OCE.

II. TECHNICAL EFFICIENCY AND OVERALL EQUIPMENT EFFICIENCY (OEE) FRAMEWORK

In manufacturing practice, especially in the case of automated production lines for mass production, the use of a key performance indicator termed as Overall Equipment Efficiency (OEE) is very popular (see Sharma et al., 2006; Dal et al., 2000). The OEE was introduced by Nakajima (1998), aimed at supporting the processes of total productivity maintenance (TPM). From the methodological point of view the OEE is a productivity metric that estimates the technical efficiency of a production process by controlling the availability, performance and quality of the production process (see Huang et al., 2003; De Ron and Rooda, 2006; Jonsson and Lesshammar, 1999) for scientific evaluation of the OEE and for the relevant analysis on the present state of the art.

There exist different varieties of the mathematical specification of an *OEE*, where the common framework is given as:

$$OEE = A \cdot P \cdot Q. \tag{1}$$

Symbols: OEE – overall equipment efficiency,
A – availability rate,
P – performance rate,
Q – quality rate.

The availability rate (*A*) measures the share of effective operating time in total operating time. The total operating time (*TOT*) is a time-span within which the production process can proceed. However, due to different reasons, the production process does not take place within the whole available time-span. Therefore, a time-span within the production process in drive is measured as an effective operating time (*EOT*). Hence, the availability rate is a relative coefficient calculated as:

$$A = \frac{EOT}{TOT}. \tag{2}$$

Symbols: A – availability rate (0 ≤ A ≤ 1),
EOT – effective operating time,
TOT – total operating time.

If a production is a smooth process without any breakdowns and stops, then the effective operating time (*EOT*) has to be in line with the total operating time (*TOT*), and the coefficient of availability (A) reaches its potential level 1. If the effective operating time diminishes, the availability rate diminishes towards its minimum level 0.

The performance rate (*P*) is a relative coefficient with an actual production speed (*APS*) in the numerator and a potential production speed (*PPS*) in the denominator. The production speed measures the amount of production in a certain time unit (for instance 1000 pieces per hour). According to this, the performance rate is calculated as:

$$P = \frac{APS}{PPS}. \tag{3}$$

Symbols: P – performance rate (0 ≤ P ≤ 1),
APS – actual production speed,
PPS – potential production speed.

In the case of full efficient production, there is no deviation between the actual and the potential production speed. However, due to various inefficiencies, there occurs the problem of speed reduction of the production process. Consequently, the actual production speed is reduced below its potential level, and the performance rate diminishes towards its minimum level 0.

The quality rate (Q) measures the share of good pieces of production in the total production realized within the effective operating time and at the given performance of the production line. According to this, the following definition equation is used when estimating the quality rate:

$$Q = \frac{TP}{TP_{\max}}. \tag{4}$$

Symbols: *Q* – quality rate (0 ≤ Q ≤ 1),
TP – actual total product (amount of good products),
TP_{max} – maximum total product (potential amount of products).

In the case of full quality production, there is no deviation between the amount of good products and the potential amount of products. However, due to various inefficiencies, the amount of good products is reduced below its potential level, and the quality rate diminishes towards its minimum level 0.

There exists an extensive amount of theoretical and empirical literature on the explanation and prediction power of *OEE* and its practicability for productivity management (see García-Cebrián and López-Viñegla, 2002; Tzu-Chuan et al., 2005; Leem and Kim, 2004; Wang et al., 2004). However, so far one important point has not been recognized enough. Namely, everything that has an influence on production has also a systematic impact on production costs. In the following section this relationship is described.

III. RELATIONSHIPS: PRODUCTIVITY – AVERAGE COSTS AND TECHNICAL EFFICIENCY – COST EFFICIENCY

Production is a technical process with a relationship between the amount of used production factors (such as energy or raw materials, working hours etc.) and the total product. Analytically these relationships are presented by the so-called technical coefficients:

$$a_i = \frac{X_i}{TP}. \tag{5}$$

Symbols: a_i – i-th technical coefficient,
X_i – amount of i-th production factor used,
TP – total product.

Note: In this case we do not distinguish between actual and potential total product.

This technical coefficient measures the amount of i-th production factor used for producing a unit of final product.

The inverse value of the technical coefficient is the average productivity of the selected production factor:

$$AP_X = \frac{TP}{X_i}. \tag{6}$$

Symbols: AP_X – average productivity of production factor X,
X_i – amount of i-th production factor used,
TP – total product.

Note: In this case we do not distinguish between actual and potential total product.

The average productivity measures the amount of total product per unit of i-th production factor X.

If we multiply the amount of the i-th production factor used by the belonging price of the production factor we obtain the costs of the i-th production factor. When adding up these partial costs, we obtain the total costs:

$$TC = \sum_{i=1}^{n} \left(X_i \cdot p_i \right). \tag{7}$$

Symbols: TC – total costs,
X_i – amount of i-th production factor used,
p_i – price of i-th production factor.

If we divide total costs by the amount of production, we obtain the so-called average costs that measure the amount of total costs per unit of product:

$$AC = \frac{TC}{TP}. \tag{8}$$

Symbols: AC – average costs,
TC – total costs,
TP – total product.

Note: In this case we do not distinguish between actual and potential total product.

If we relate average productivity (6) with average costs (8), keeping the price of production factor used constant, we can deduce the relationship between average productivity and average costs as follows: "*An increase of the AP_x demonstrates growth of TP by keeping the amount of production factor used unchanged. Consequently, the numerator in equation (8) is unchanged and the denominator is higher, thus causing a decrease of the AC, and vice versa.*" This demonstrates the inverse relationship between average productivity and average costs.
However, the focus of our analysis is not on average productivity and average costs, but on the relationship between technical efficiency and cost efficiency. For this purpose we have to introduce optimality criteria. In the case of average productivity, the optimality criterion is the highest possible amount of production per i-th production factor used. In the case of average costs this criterion is the lowest possible costs per unit of product. Hence, we have to distinguish between potential and actual productivity and between potential and actual average costs. Graphically this issue is presented in the Figure 1.

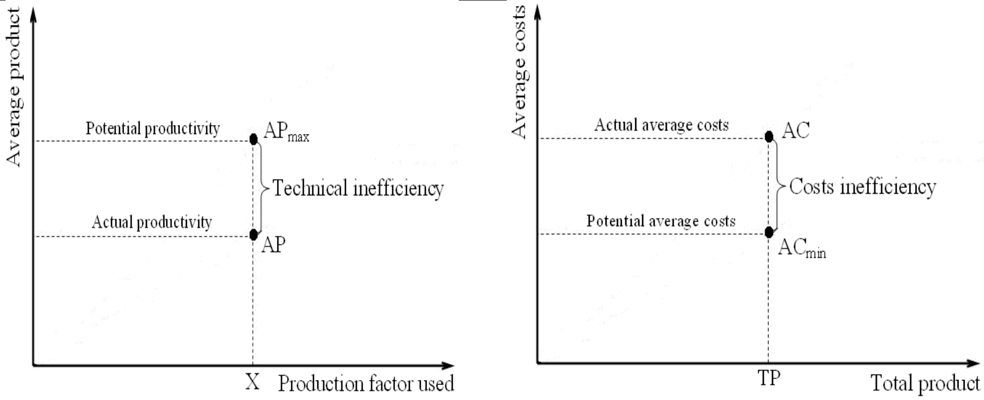

FIGURE 1: TECHNICAL AND COST INEFFICIENCY

Source: Own composition.

On the left side of Figure 1 the graphical deduction of technical inefficiency is presented. The amount of production factor used equals X and is related with the average productivity at the *AP* level. However, the actual productivity level is below the potential productivity (AP_{max}). The potential productivity level is reached in specific cases when full availability $(A=1)$, maximal performance $(P=1)$ and full quality $(Q=1)$ are jointly reached. There are numerous inefficiency factors which reduce the availability and/or performance and/or quality, and cause the decrease of actual productivity below the potential productivity. The distance between actual and potential productivity is termed as technical inefficiency.
At this point it is important to highlight two different terms with equal meaning. In the literature two terms are used: technical inefficiency and technical efficiency, where both measure the difference between actual and potential productivity. In our case we recommend using the term technical efficiency rate, which does not measure the difference between actual and potential productivity, but rather the ratio between actual and potential productivity as follows:

$$TER = \frac{AP}{AP_{max}}. \quad (9)$$

Symbols: *TER* – technical efficiency rate, $0 \le TER \le 1$,
AP – actual average productivity,
AP_{max} – potential (maximum) average productivity.

If AP equals AP_{max} then TER equals 1, implying full technical efficiency – actual amount of production equals the potential amount of production.
On the right side of Figure 1 the graphical deduction of cost inefficiency is presented. The obtained cost inefficiency is the consequence of technical inefficiency. Namely, in the case of the production process analyzed in Figure 1 the amount of production factor used equals X. If this amount of production factor used is related to the potential productivity, then the lowest possible average costs are reached. When actual productivity is below the potential one, average costs are above the potential level. The distance between actual and potential average costs is termed as cost inefficiency.
In this case it is important to highlight two different terms with equal meaning: costs inefficiency and costs efficiency, where both measure the difference between actual and potential average costs. In our case we recommend using the term costs inefficiency rate, which does not measure the difference between actual and potential average costs, but rather the ratio between actual and potential average costs as follows:

$$CIR = \frac{AC}{AC_{\min}}. \quad (10)$$

Symbols: CIR – cost inefficiency rate, $1 \leq CIR \leq \infty$,
AC – actual average costs,
AC_{min} – potential (minimum) average costs.

If AC equals AC_{min}, then CIR equals 1, implying zero cost inefficiency (or full costs efficiency) that can be achieved only in the case of full technical efficiency. If technical efficiency diminishes towards zero, costs inefficiency rises towards ∞. Namely, technical efficiency at value zero implies TP = 0. As we know from (8), actual average costs are calculated as the ratio between total costs (in numerator) and total product (in denominator). When total product equals 0, the value of actual average costs expands towards ∞. Hence, the value zero of technical efficiency (i.e. full technical inefficiency) is related with infinite cost inefficiency.

Now, since the definition equations for technical efficiency rate (*TER*) and cost inefficiency rate (*CIR*) have been established, their co-domains can be deduced.

- The co-domain of the technical efficiency rate (*TER*) is the interval [0, 1]. Rate 0 is reached if the actual amount of production equals 0, and level 1 is reached if the actual amount of production equals the potential amount of production (i.e. actual productivity equals potential productivity).
- The co-domain of the cost inefficiency rate (*CIR*) is the interval [1, ∞). Rate 1 is reached when actual average costs equal potential average costs. This can be reached in specific cases when actual productivity equals potential productivity. However, if technical efficiency diminishes away from its potential level, average costs rise above the potential ones. As described in the previous paragraph, zero technical efficiency causes infinite cost inefficiency. Therefore, the co-domain of cost inefficiency rate has no upper frontier.

According to the results discussed, two conclusions which demonstrate the inverse relationship between technical efficiency and cost inefficiency can be deduced:

- If technical efficiency rises towards 1, cost inefficiency decreases towards 1.
- If technical efficiency decreases towards 0, cost inefficiency grows towards ∞.

Although the cost inefficiency is the consequence of the reached technical efficiency, the existing methodological frameworks do not estimate cost inefficiency directly from observed technical efficiency. We recognized this problem by conducting several applicative researches for companies that perform automated production processes and measure their technical efficiency in real time by using *OEE* methodology. It is in fact this extensive use of the *OEE* framework in industrial management that raises the question of how to obtain cost inefficiency measurements directly from *OEE* in real time. For this purpose we conduct extensive theoretical and applicative researches with the aim of developing new algorithm that provides the answer to the stated question – we have developed an algorithm that estimates cost inefficiency rates directly from the technical efficiency rates obtained.

IV. OVERALL COST EFFICIENCY (OCE)

The term Overall Cost Efficiency (*OCE*) was proposed by us (Novak and Žižmond, 2011). We proposed the name according to the fact that this parameter is deduced from the key performance indicator *OEE* that measures overall equipment efficiency (or the so-called technical efficiency).

A. OCE - Algorithm aimed at transforming technical efficiency into cost inefficiency

In microeconomic analyses of the cost function we have to distinguish between fixed and variable costs. Fixed costs are independent of the production amount, while variable costs vary with the production amount. Typical fixed costs are for example costs of labour force: we have to pay the worker for his daily work, although the machine was operating only a half of his working time. This has an influence on fixed costs per unit of the product, which are mathematically calculated as:

$$AFC = \frac{FC}{TP}. \tag{11}$$

Symbols: *AFC* – average fixed costs,
FC – fixed costs,
TP – actual total product.

Following the above specified definition equation of average fixed costs, we can establish that *AFC* continuously diminish towards 0 if TP increases towards ∞.
On the other hand, costs of material are typical variable costs, since the consumption of material depends on whether the machine is in operating position or not. Therefore the average variable costs are constant per unit of final product. Mathematically they are calculated as:

$$AVC = \frac{VC}{TP}. \tag{12}$$

Symbols: *AVC* – average variable costs,
VC – variable costs,
TP – actual total product.

If we sum up average fixed costs and average variable costs, we obtain average costs:

$$AC = \frac{TC}{TP} = \frac{FC + VC}{TP} = \frac{FC}{TP} + \frac{VC}{TP} = AFC + AVC. \tag{13}$$

Symbols: *AC* – average costs,
TC – total costs,
TP – total product,
FC – fixed costs,

VC – variable costs,
AFC – average fixed costs,
AVC – average variable costs.

Note: In this case we do not distinguish between actual and potential total product.

When deducing *OCE* from *OEE* we have to be aware that changes in availability (*A*), performance (*P*) or quality (*Q*), which determine the *OEE*, differently impact production costs. If we accept the above described system of average fixed and average variable costs, the following axioms about the impact of availability, performance and quality on average costs can be defined:

- Decreasing availability (*A*) raises average fixed costs, while average variable costs remain unchanged. As we know from (2), the decreasing availability is a consequence of decreasing effective operating time. The decreasing effective operating time-span has no impact on the consumption of variable production factors (such as raw materials, or energy). The only consequence is reduced actual total product – the actual amount of production is below the potential level. Since fixed costs remain unchanged, the diminishing total product causes growth of average fixed costs – see (11). Hence, the changes of availability cause changes of average costs only via changes of average fixed costs.
- Decreasing performance (*P*) raises average fixed costs, while average variable costs remain unchanged. Following the definition equation of performance rate (3), the decreasing performance is a consequence of the decreasing actual production speed. The decreasing actual production speed has no impact on the consumption of variable production factors. Hence, the only consequence is reduced total product – the same impact as this occurs in the case of reducing availability. Therefore, the changes of performance cause changes of average costs only via changes of average fixed costs.
- Decreasing quality (*Q*) raises average fixed costs as well as average variable costs. The decreasing quality rate implies growth of the amount of bad pieces of production in the total product. Therefore the actual amount of production is below the potential one, which causes, according to definition equation (11), growth of average fixed costs. However, production of bad pieces of production has also an influence on average variable costs. When calculating the actual average costs we have to multiply the costs of variable production factors inherent to good pieces also with costs of variable production factors inherent to bad pieces. Hence, changes of quality have additional effects on cost inefficiency. The first impact is via increasing average fixed costs (as in the case of availability and performance), and the second impact is via average variable costs.

So, generally, changes in availability rate and performance rate influence only average fixed costs, while quality rate has an impact on average fixed costs as well as on average variable costs. These facts are an integral part of the *OCE* algorithm proposed below. By evaluating the algorithm we have to be aware about definition of the following symbols:

TP – actual total product,
A – availability rate,
P – performance rate,
Q – quality rate,
TC – total costs,
VC – variable costs,
FC – fixed costs,
AC – average costs,
AFC – average fixed costs,
AVC – average variable costs,

min – minimum,
max – maximum.

We start the development of the *OCE* algorithm by using the definition equation of cost inefficiency rate (10), and introduce some rearrangements by using (11), (12) and (13):

$$CIR = \frac{AC}{AC_{\min}} = \frac{\left(\frac{FC}{TP}\right) + \left(\frac{VC}{TP}\right)}{\left(\frac{TC_{\min}}{TP_{\max}}\right)} = \frac{\left(\frac{FC}{TP}\right) + \left(\frac{VC}{TP}\right)}{\left(\frac{FC}{TP_{\max}}\right) + AVC_{\min}}. \tag{14}$$

Note: The condition AVC_{min} implies full quality.

If we introduce *OEE* into (14), we transform *CIR* into the *OCE* algorithm that calculates costs inefficiency from technical efficiency (*OEE*):

$$OCE = \frac{\left(\frac{FC}{TP_{\max} OEE}\right)}{\left(\frac{TC_{\min}}{TP_{\max}}\right)} + \left(\frac{AVC}{AFC_{\min} + AVC_{\min}}\right). \tag{15}$$

Note: TP_{max} multiplied by availability rate (*A*), performance rate (*P*) and quality rate (*Q*), i.e. with OEE, gives actual total product (*TP*).

$$OCE = \frac{\left(\frac{AFC_{\min}}{OEE}\right)}{AC_{\min}} + \left(\frac{AVC}{AFC_{\min} + AVC_{\min}}\right)$$

$$= \frac{1}{OEE} \cdot \frac{AFC_{\min}}{AC_{\min}} + \frac{AVC}{AC_{\min}}. \tag{16}$$

The equation (16) is the first definition equation of our algorithm aimed at transforming technical efficiency measured on the basis of *OEE* into cost inefficiency measurement. The term $\frac{1}{OEE}$ implies the known inverse relationship between technical efficiency and cost inefficiency.

However, *AVC* can be expressed also as:

$$AVC = \frac{VC}{TP} = \frac{AVC_{\min} \cdot TP_{\max} \cdot A \cdot P}{TP_{\max} \cdot A \cdot P \cdot Q} = \frac{AVC_{\min}}{Q}. \tag{17}$$

By introducing (17) into the (16) we can deduce the final *OCE* algorithm:

$$OCE = \frac{1}{OEE}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \left[\frac{\left(\frac{AVC_{\min}}{Q}\right)}{AC_{\min}}\right] = \tag{18}$$

$$= \frac{1}{OEE}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \frac{1}{Q}\left[\frac{AVC_{\min}}{AC_{\min}}\right].$$

The equation (18) is the final solution to our research problem. As we can see, there is an inverse relationship between *OCE* and *OEE*, where quality rate has an additional impact via variable costs. The specification (18) is a mathematically deduced estimator that transforms technical efficiency into cost inefficiency in real time. There are four factors that determine the impact of technical efficiency on cost inefficiency:

- The first impact is controlled by the inverse value of *OEE* ($0 \leq OEE \leq 1$). Therefore, if *OEE* diminishes towards 0 the inverse value of *OEE* rises towards infinity, and if *OEE* rises towards 1, its inverse value diminishes towards 1.
- The second impact is controlled via the share of fixed costs in total costs. The domain of this ratio is [0, 1] – it is zero if total costs are variable, and it is 1 if total costs are fixed costs. The greater the share of fixed costs in total costs, the higher the impact of technical efficiency on cost inefficiency.
- The third impact is controlled via the inverse value of quality rate. The domain of the inverse ratio is between $[1, \infty)$. It is 1 in the case of full quality, while decreasing quality rate causes its growth towards ∞.
- The fourth factor is controlled via the share of average variable costs in average costs. The domain of this share is between [0, 1] – it is zero if total costs are fixed costs, and it is 1 if total costs are variable costs.

According to the developed algorithm, the above described four separate factors are actually united into two impacts that jointly determine the value of *OCE*.

- The first one is the impact of *OEE* jointly with the share of fixed costs in total costs. This implies that *OEE* determines the cost inefficiency only via fixed costs.
- The second one is impact of quality rate jointly with the share of variable costs in total costs.

This implies that all of the parameters incorporated in *OEE* have a unique impact on costs inefficiency via the fixed costs, but the quality rate parameter has an additional impact on cost inefficiency via the variable costs.

The equation (18) is also suitable for application in industry practice. According to the proposed algorithm only data on the shares of fixed and variable costs in average costs are needed. Since those shares are known from the normative calculations of average costs, the equation (18) is suitable for application in industrial management.

B. Impact of OEE's parameters on average costs – further analysis

The above described separate impacts of technical efficiency on costs inefficiency are axioms that have to be submitted to theoretical analysis. We provide a decomposition of impact of separate *OEE*'s parameters on average costs.

We start this decomposition with an analysis of the impact of availability rate (A) on average costs. The average costs are calculated as the ratio between total costs and total product (8). Since total costs consist of variable and fixed costs, average costs can be also calculated as the sum of average fixed costs and average variable costs, where average fixed costs are continuously diminished as the production amount expands and average variable costs remain constant. Hence, if we know the maximum amount of production, we can calculate minimum average fixed costs. Mathematically we describe this tendency by using the following expressions:

$$AFC = \frac{FC}{TP}, \text{ and } AFC_{\min} = \frac{FC}{TP_{\max}}, \tag{19}$$

$$\text{if } TP \Rightarrow TP_{\max} \Leftrightarrow AFC \Rightarrow AFC_{\min}.$$

The implication (19) postulates that we can achieve the minimum average fixed costs only if the actual amount of production is in line with its potential amount. By using the implication (19), we can explain the impact of availability rate (*A*). The availability rate (*A*) measures a share of effective time that was productively used in the total time disposable for production – see equation (2). When the availability rate increases towards 1 the effective time that was productively used approaches towards total disposable time. Consequently, increasing availability rate enables the increase of the actual amount of production towards the potential amount that causes the decrease of average fixed costs towards their potentially lowest value. Hence, if

$$A \Rightarrow 1 \Leftrightarrow TP \Rightarrow TP_{\max}, \text{ consequently } AFC \Rightarrow AFC_{\min}. \tag{20}$$

If we conjoin (19) and (20) we can conclude that the change of availability rate changes only the average fixed costs, where it holds that: growth of availability rate decreases the average fixed costs towards their potentially lowest value, and vice versa.

Next, we have to conduct the decomposition about the impact of performance rate (*P*) on average costs. With definition equation (3), the performance rate compares the actual production speed with the potential production speed. As the production speed measures the amount of production in a certain time unit, the performance rate actually compares the actual amount of production with the potential amount of production that can be produced within the total operating time that is used productively. So, the performance of the production process focuses only on the so-called effective operating time. Each production line has its potential speed and, due to different inefficiencies, in reality the actual speed is usually below its potential level. Hence, the decrease of the performance rate causes the decrease of the actual amount of production from its potential level, and vice versa. From (19) we already know the impact of divergence between the actual and potential amount of production on average fixed costs. Therefore we can conclude:

$$\text{if } P \Rightarrow 1 \Leftrightarrow TP \Rightarrow TP_{\max}, \text{ consequently } AFC \Rightarrow AFC_{\min}. \tag{21}$$

Finally we have to explain the additional effect of quality rate (*Q*) on average costs. Additional because, as we can deduce from (18), the quality rate impacts average costs via the impact of *OEE* on average fixed costs, and additionally via the average variable costs.

The explanation of quality rate's impact via average fixed costs on *OCE* has the same background as in the case of availability rate and performance rate. Since the quality rate measures the share of good pieces of production in the whole amount of production, we know that diminishing quality rate causes divergence of the actual amount of production from the potential amount. The impact of this divergence process on average fixed costs is already known from (20) and (21), where in this case the divergence is caused by the quality rate (*Q*):

$$\text{if } Q \Rightarrow 1 \Leftrightarrow TP \Rightarrow TP_{max}\text{, consequently } AFC \Rightarrow AFC_{min}\text{.} \qquad (22)$$

According to the equation (18), the second impact of quality rate on *OCE* is via variable costs. In this case the impact of quality rate is not incorporated into *OEE*, but has a direct impact via the share of variable costs in total costs. Formally we describe this impact via variable costs as follows:

$$AVC = \frac{VC}{TP},\ AVC_{min} = \frac{VC_{min}}{TP} \text{ and } Q = \frac{TP}{TP_{max}}. \qquad (23)$$

$$\text{If } Q \Rightarrow 1 \Leftrightarrow TP \Rightarrow TP_{max}, \text{ consequently } VC \Rightarrow VC_{min} \Leftrightarrow AVC \Rightarrow AVC_{min}.$$

This additional impact rises from the fact that, when producing a bad piece of production, this means that we have used materials, energy and other constitutional parts of the product, but in the end this product was unusable. When producing a product of an unsatisfactory quality we have not only consumed a part of the productive time, but we have also consumed materials that should be used in the production of products of an acceptable quality.

C. Relationship between OEE and OCE

Since we have explained the individual effects of *OEE*'s parameters on *OCE*, the analysis on the relationship between *OEE* and *OCE* has to be performed. For this purpose we have to remember the descriptions of technical efficiency (measured via *OEE*) and cost inefficiency (measured via *CIR*). We have pointed out that the growth of technical efficiency implies increase of OEE towards 1, meaning that production approaches towards full utilization of production capacities. Furthermore, the growth of technical efficiency causes decrease of costs, which implies decrease of the $CIR = \frac{AC}{AC_{min}}$ ratio towards 1. Since we have developed our *OCE* algorithm, that aims to transform technical efficiency into costs inefficiency also from the *CIR* ratio $\left(\frac{AC}{AC_{min}}\right)$, the growth of *OEE* towards 1 has to cause decrease of *OCE* towards 1. And when *OEE* equals 1, *OCE* also has to equal 1.

To prove these relations we have to take the separate parts of *OCE* algorithm into consideration by considering the ratio between average fixed and average variable costs as constant. This is necessarily due to the fact that also changes in shares of average fixed and average variable costs in average costs influence the *OCE* – see definition equation (18).

The increase of *OEE* towards 1 can be achieved on the basis of the increase of availability rate, performance rate and quality rate towards 1:

$$OEE \Rightarrow 1 \Leftrightarrow A \Rightarrow 1 \wedge P \Rightarrow 1 \wedge Q \Rightarrow 1. \quad (24)$$

If *OEE* increases towards 1, and *Q* also increasestowards 1, the inverse value of quality rate decreases towards 1:

$$OEE \Rightarrow 1 \wedge Q \Rightarrow 1 \Leftrightarrow \frac{1}{Q} \Rightarrow 1. \quad (25)$$

If we substitute (24) and (25) into (18) we obtain:

$$OCE = \frac{1}{OEE}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \frac{1}{Q}\left[\frac{AVC_{\min}}{AC_{\min}}\right], \text{ where } OEE \Rightarrow 1 \text{ and } \frac{1}{Q} \Rightarrow 1, \quad (26)$$

therefore

$$OCE = \frac{1}{1}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \frac{1}{1}\left[\frac{AVC_{\min}}{AC_{\min}}\right] = \frac{AFC_{\min} + AVC_{\min}}{AC_{\min}} = \frac{AC_{\min}}{AC_{\min}} = 1.$$

From (26) we can deduce the conclusion that *OCE* reaches value 1 only in case when OEE reaches value 1 – furthermore, if OEE equals 1, also *Q* and its inverse value have to equal 1.
There is also an opposite possibility: the decrease of *OEE* towards 0 causes the increase of *OCE* away from 1 towards ∞. The decrease of *OEE* towards 0 is caused by the decrease of at least one parameter that constitutes *OEE* towards 0. We then have the following four possibilities.
First, the availability rate decreases towards 0, while performance rate and quality rate equals 1. In this case it holds:

$$OCE = \frac{1}{OEE}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \frac{1}{Q}\left[\frac{AVC_{\min}}{AC_{\min}}\right], \quad \text{where} \quad OEE \Rightarrow 0, \quad (27)$$

$A \Rightarrow 0$, $P = 1$ and $Q = 1$, therefore $\frac{1}{OEE} > 1$, and consequently $OCE > 1$.

Symbols: *OCE* – overall cost efficiency,
OEE – overall equipment efficiency,
AFC – average fixed costs,
AC – average costs,
AVC – average variable costs,
A – availability rate,
P – performance rate,
Q – quality rate,
min – minimum.

Second, performance rate decreases towards 0, while availability rate and quality rate equals 1. In this case it holds:

$$OCE = \frac{1}{OEE}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \frac{1}{Q}\left[\frac{AVC_{\min}}{AC_{\min}}\right], \quad \text{where} \quad OEE \Rightarrow 0, \quad (28)$$

$P \Rightarrow 0$, $A = 1$ and $Q = 1$, therefore $\frac{1}{OEE} > 1$, consequently $OCE > 1$.

Symbols: *The same as for the equation (27).*

Third, quality rate decreases towards 0, while availability rate and performance rate equals 1. In this case it holds:

$$OCE = \frac{1}{OEE}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \frac{1}{Q}\left[\frac{AVC_{\min}}{AC_{\min}}\right], \quad \text{where} \quad OEE \Rightarrow 0, \tag{29}$$

$Q \Rightarrow 0$, $A = 1$ and $P = 1$, therefore $\frac{1}{OEE} > 1$ and $\frac{1}{Q} > 1$, hence $OCE > 1$.

Symbols: *The same as for the equation (27).*

Fourth, availability-, performance- and quality rate decrease towards 0. In this case it holds:

$$OCE = \frac{1}{OEE}\left[\frac{AFC_{\min}}{AC_{\min}}\right] + \frac{1}{Q}\left[\frac{AVC_{\min}}{AC_{\min}}\right], \quad \text{where} \quad OEE \Rightarrow 0, \tag{30}$$

$A \Rightarrow 0$, $P \Rightarrow 0$ and $Q \Rightarrow 0$, therefore $\frac{1}{OEE} \Rightarrow \infty$,consequently $OCE \Rightarrow \infty$.

Symbols: *The same as for the equation (27).*

Following the conclusions from (30) it is obvious that costs inefficiency has no upper limit, but we can reduce the costs inefficiency through the increase of technical efficiency. Technical efficiency is the internal factor of potential development of a company. In the recent literature especially from business sciences and management we can establish the tendency that authors recognize that management fully exhausts the external factors and lies internal potential unexhausted (see for instance Jagrič and Bekő, 2009; Vukasovič, 2009; Jerman et al., 2009; Stubelj, 2009; Dolenc and Laporšek, 2011; Vehovar and Lesjak, 2007). *OEE* is appropriate framework aimed at measuring the internal potential, however obviously it is not efficiently applied into the industrial management praxis. The proposed OCE framework should increase the interest on application of OEE and especially, it should be a framework that adds value to the management decision making.

Therefore we conclude the article in the following section by presenting the OCE from industrial management point of view.

V. INSTEAD OF CONCLUSION: OCE FROM INDUSTRIAL MANAGEMENT POINT OF VIEW

From the industrial management point of view, two groups of main conclusions can be established.

First, the proposed new key performance indicator (KPI), termed as *OCE*, is an efficient tool that enables production management to control for cost efficiency of the production process in real time. By using the proposed *OCE* algorithm we can evaluate each factor that causes technical inefficiency of the production process from the costs point of view. Once we have the *OEE* measures we can deduce OCE measures that inform us by what percentage production is more expensive than it can be in the case of full technical efficiency.

Second, although there is a systematic and inverse relationship between technical efficiency and cost inefficiency, this relationship is not unique, but heterogeneous. Two simple examples can demonstrate this issue.

Example 1	**Example 2**
$A=1,\ P=1,\ Q=0.8,$	$A=0.8,\ P=1,\ Q=1,$
consequently $OEE=0.8,$	consequently $OEE=0.8,$
and if $\frac{AVC_{\min}}{AC_{\min}}=\frac{AFC_{\min}}{AC_{\min}}=0.5$,	and if $\frac{AVC_{\min}}{AC_{\min}}=\frac{AFC_{\min}}{AC_{\min}}=0.5,$
$OCE=\frac{0.5}{0.8}+\frac{0.5}{0.8}=1.25.$	$OCE=\frac{0.5}{0.8}+\frac{0.5}{1}=1.125.$

In both cases *OEE* equals 0.8, implying that the actual amount of production reaches 80% of the potential amount of production. But, in the first case the *OCE* equals 1.25, which implies that actual average costs (i.e. costs per unit of total product) are 25% higher than they are in the case of full technical efficiency. And in the second case the *OCE* equals 1.125, implying that actual average costs are by 12.5% higher than they are in case of full technical efficiency.

So the same level of technical efficiency is related to different levels of cost inefficiency. And exactly this heterogeneous nature of the causal relationship between *OEE* and *OCE* is the basic argument in favour of introducing *OCE* in the industrial management praxis. This is inevitable, because efficiency improvements demand additional investments and, as we have demonstrated, it is quite possible that we may achieve large improvements in technical efficiency but will achieve only a small reduction in cost inefficiency. Therefore an efficient and successful industrial management needs to upgrade the *OEE* framework with the proposed *OCE* methodology.

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UKUPNA TROŠKOVNA EFIKASNOST

Sažetak: S obzirom na trenutno stanje stvari u okviru optimizacije proizvodnje, najpopularnija je metodologija ukupne efikasnosti opreme (OEE). Ipak, ova metodologija pristupa optimizaciji proizvodnje samo sa stajališta tehnologije dok ignorira ekonomski aspekt. Zato smo razvili novi ključni indikator performanse, ukupnu troškovnu efikasnost usmjerenu na mjerenje troškovne efikasnosti proizvodnog procesa u realnom vremenu. Njegova je primjena zasnovana na mjerenjima ukupne efikasnosti opreme i korisna je za primjenu u praksi industrijskog menadžmenta. Upotrijebili smo uobičajeno matematičko modeliranje u kombinaciji s deskriptivnim tehnikama mikroekonomske analize.

Ključne riječi: tehnička efikasnost, troškovna efikasnost, produktivnost, mikroekonomija, industrijski menadžment