Mining machines effectiveness and OEE Indicator

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Abstract. The situation in the hard coal industry in Poland is forcing the identification of effective and practical indicators of the effectiveness of machinery and equipment. In the article, the authors discuss the possible use of the OEE indicator for the evaluation of production processes in hard-coal mines. In summary, recommendations are made to enable efficiency assessment of mining machinery using the OEE.

1. Introduction

Eliyahu Goldratt [1] noted that good methods and tools in the management of business and manufacturing used in several Japanese car factories proved to be ineffective in others. The main cause of these setbacks was found to be the difference in the processes and technologies employed by the latter, in comparison to the processes performed in the automotive industry.

Effectiveness in the employment of available resources in industrial processes, including human labor and technical equipment, in order to achieve efficiency is one of the basic management objectives, particularly with regards to operational management.

Mining processes have for many years been treated as production processes and attempts have been made for an equally long time, to implement methods and management tools transferred from other types of business, not just industrial ones [2]. Professor Bolesław Krupiński, a prominent Polish mining expert, paid close attention to the fact that mining processes are of a different nature, namely: "... the mine is, first and foremost, a great transport undertaking ...". Disparity between the processes used in extraction from those in production is one of the reasons for the failure of management methods derived from the Japanese car industry, when implemented in mining [3]. Still, hard coal mines are attempting to implement tools and methods, including diagnostic tools and methods, which will not only be ultimately useless but will also drain unnecessary resources from their implementation. The reason for this lies in the differences between both process systems.

One such attempt is in the employment of the Overall Equipment Effectivness (OEE) tool for evaluation of machine efficiency [4]. This indicator is an effective tool for evaluating the use of machines in production plants and is geared towards the diagnosis of machinery utilisation in the manufacturing process, i.e. at the part of the process system that is adapt towards the external customer, creating added value for the company. In production processes, especially in manufacturing, the high degree of utilisation of each machine in the area of primary production is one of the conditions of process efficiency [5]. In underground mines the basic process is the mining process, which involves extraction and transport processes related to the transport of minerals [6]. Both extraction and transport processes may be mechanized in different ways. Technical solutions and the organisation of work used in the extraction of minerals such as hard coal and the manner in which it is
mechanised significantly affect the degree to which individual machines are utilised. It is important to note that the use of different evaluation criteria (indicators) is indicated by the theoretical and practical experiences of large mining companies in the world [7, 8].

2. OEE indicator

The Overall Equipment Effectiveness (OEE) rating is one of the Key Performance Indicators (KPIs) used in the TPM (Total Production Maintenance) system. This is an indicator of the equipment effectiveness used in the area of operational production management. Pioneering the implementation of TPM was the Japanese company Denso, which is part the Toyota Group, thus belonging to the automotive industry. The TPM system, being an element of Lean Management, consists of the preventative maintenance of machinery and equipment within the company by operators (autonomous maintenance) and maintenance personnel (scheduled maintenance). Adequate cooperation between maintenance and production allows for an improvement in the efficiency of even heavily used machinery and a significant reduction in hazards such as machinery breakdown, or unplanned downtime. Consequently, this serves to improve the efficiency of the manner in which machines and equipment are utilised.

OEE is the product of 3 other simpler indicators:

\[
OEE = \text{Availability} \times \text{Performance} \times \text{Quality} \tag{1}
\]

where:

- **Availability** - The ratio of the time planned for a production task to the time that can actually be devoted to this task. Availability is reduced by machine down time stemming from breakdowns, retooling and the setting up of machinery (and according to the adopted method), as well as by the loss of speed of operation.

- **Performance** – the ratio of availability to operating time.

- **Quality** – the ratio of good and defective units produced to all units produced.

Figure 1 shows the OEE indicator in pictorial form.

![Figure 1. OEE structure (Source: according to [5])](image-url)
processes. Despite being composed of machinery and equipment, the use of the OEE indicator encounters significant problems in unit production.

It should be noted that the production process most often takes place in predetermined physical conditions (e.g., in buildings isolated from weather conditions), so the impact of typically natural conditions is negligible. A well-designed production system should work continuously during its operating time, and the drop in availability should result solely from breakdowns. Falls in equipment utilization are mainly a consequence of:

- "bottle-necks" (restrictions),
- failures in the provision of raw materials,
- other organisational failures.

Owing to the characteristics of this indicator, the question arises as to whether the OEE indicator can be used effectively to assess the efficiency of machinery and equipment in hard coal mining.

3. Process systems in underground mining

Durlik [9] recognizes the basic process in a mine to be extraction, therefore making it a production process. However, using a commonly used classification of processes in an enterprise, with divisions into primary processes, ancillary processes and management processes [10], it should be noted that in a mine, the primary process is not a production process in this sense. The extraction process does not create the usefulness of the shape (character) of the material, which is typical for a production process.

For the external customer (the receiver of the process result), the extraction process creates the usability of space and time that is typical for logistic processes [6]. In the extraction process, sub-processes are not involved. These, however, form a key component in production processes. The share of operations of a technological nature (change of shape or physical or chemical properties) in the entire system of processes in a mine, i.e., complex structure of activities, is small.

![Figure 2. The primary process overall – the extraction process in a mine (based on [6]).](image)

The basic process in the mining sector, i.e., the mining process, includes the sub-processes of excavation and transport of the extraction material (figure 2). It should be noted that the transport of waste can be performed in a continuous system (e.g., conveyor belt, etc.), intermittent (vehicles, rail or shaft lift) or mixed. Particularly in terms of intermittent transport, there is usually a return drive element (unladen) that is difficult to define in the performance index of OEE equipment. It is difficult to indicate a uniform quality meter when transporting waste. By concentrating on the mining aspect of...
the core process of a mine, i.e. the mining process (excavation works + transport of the output), the mining process can be defined as: ‘Emptying the mineral store previously accumulated by means of natural processes and supplying this mineral to the end user (external customer)’ [6].

The mining process is only one of the components of a complex network of mine processes, as shown in figure 3. In this figure, the process of refining/enrichment of the mineral has been omitted as it is not always performed in a mine.

![Diagram](https://example.com/diagram.png)

**Figure 3.** A generalised model of the mining process network.

Depending on the local conditions and constraints, as well as legal regulations and economic opportunities, different excavation systems are used in underground mining. Despite the variety of excavation processes, the basic cycle is shown in figure 4.

![Diagram](https://example.com/diagram.png)

**Figure 4.** Basic continuous cycle of activities in the excavation process.

Differences in the selection of mining systems in underground mines also depend on the technology of individual actions and the degree to which they are mechanised. As an example, it is possible to say that today, excavation by hand also involves the use of mechanical tools, explosive materials (blast-hole drilling with manual tools, drilling machinery and, the rarely used, hydraulic excavation). Some mining methods impose a serial organisation of work (e.g., in the case of explosive materials), which, in the case of machinery and specialised equipment performing a single operation, results in a low, although reasonably justified, degree of exploitation which deteriorates one of the elements of the OEE.
4. Basic mechanisation systems in mining and the extent to which machinery and equipment is used

As mentioned in the previous section, traditional mining methods are still used in underground mining (by hand with only perhaps mechanised tools), partly mechanised with certain operations or actions being mechanised, and fully-mechanised systems.

In traditional and partially mechanised systems, operations are performed in series - sequentially, which results in lower use of machinery and equipment, and in addition, these do not determine the final outcome of the process.

Owing to the geological and mining conditions (including the construction of deposits and natural and technical hazards), the type of rock being excavated (soft, such as salt or coal, and hard, such as metal ores) various technical solutions, including the degree and method of mechanisation of processes are used, and within these - the basic process, here being the extraction process (including the excavation process and processes / operations pertaining to the transport of the output). According to the selection criteria for technical solutions, there are three mechanisation systems in mining (two basic and additional - indirect) [11]:

- A system based on independent (autonomous) systems for the implementation of each particular unconnected operation - in excavation processes such systems are used in room & pillar excavation with conventional softrock mining using explosives, such as in the excavation of coal and some chemical raw materials, and hardrock mining such as metal ores etc. In these, mostly multiprocessor systems, each of the operations carried out in a given process is performed in series by a single specialised machine, working several pit-faces at one time. Among others, this is done in order to increase the utilisation of these machines. This requires successive movement of a given machine from process to process. The range of the process is most often limited by the effective blasting work (figure 5).

![Figure 5](https://www.youtube.com)

The important feature of these mechanisation systems is the preparation of the excavation sites with the same set of autonomous machines as the subsequent excavation machinery. Machines belonging to the autonomous system reach the place of their work autonomously.

- A spatially coherent system, constituting of a single structural unit whose sub-assemblies perform individual operations. The most well-known excavation system of this type is fully-
mechanized longwall mining (mining by continuous miners or shearers) used to extract soft minerals buried in brown coal, coke coal or potassium salts. The system consists of a milling machine (planer or milling machine), a mechanised wall casing, a scraper conveyor belt with a crusher, as well as a power and control device (figure 6).

![Figure 6. Continuous Miner as an example of a fully integrated mechanised system, in which sub-systems perform individual operations.](image)

A distinguishing feature of these systems is the necessity to perform preparatory work with other technical systems (fully or partially mechanised). A separate system is also required for the supply (in elements) and assembly of the complex wall components and the reverse operation after the completion of the excavation of the section of the wall.

- Combined systems in which some of the systems are joined into a structural whole. This group includes, first and foremost, room & pillar systems using machinery such as Continuous Miners. These machines work the pit face, load the output and transport it away from the longwall to the transport vehicle (shuttle car, haul dumper or scoop loader) at several subsequent pit faces (usually 5). Such systems are used in coal mining and in the mining of rock salt, potassium and other chemical raw materials. In addition, the machinery forming part of the mechanised systems travel autonomously to the pit face and all preparatory work is performed by the same machinery.
The room & pillar system (figure 7) with multi-functional machinery - a continuous miner is used without a casing (potassium salts) or with roof bolt anchors provided by as a separate function by a different machine (autonomous anchor which is wheel or caterpillar propelled). Multifunctional coal mining machinery differs from similar machines used in the mining of potassium salts, although they perform the same functions. The range of these particular mechanization systems, the output of the mining machine - the continuous miner is usually determined by the allowable size of the exposed roof, without the need to secure it.

5. A selection of indicators and tools for the analysis of productivity applicable to mining

Indicator formulas should be set at the central level and reflect the control and implementation status of the strategic and operational objectives set. Among these are performance measures such as [12]:

- general performance,
- pit capacity,
- overall economic efficiency - defined as the ratio of sales revenue to the total number of employees,
- economic viability - defined as the ratio of sales revenue to the number of pit workers.

Productivity is defined as the relationship between received effects and the resources needed to achieve this. With productivity defined in this manner, it is possible to employ different groups of indicators in the analysis of both technical and economic aspects [13]. Some indicators of productivity analysis used in mining include [12]:

- productivity index of fixed assets (for example, daily output from a single wall in which mineral extraction is performed by a single set of autonomous machines,
- utilisation rate of machinery and equipment,
- technical and technological parameters of machines and equipment,
- an indicator linking the operational time and technical and technological parameters of machinery and equipment,
- technical equipment indicator,
- energy equipment indicator,
- indicator of technical and operational readiness of machines and equipment in excavations,
- index of utilisation of the technical capacity of machines and equipment in excavation works,
- capacity utilisation index of a wall.

Owing to the different mineral extraction technologies and different mining engineering systems, the indicators mentioned above have different forms adapted to specific processes and technical devices.

For example, the degree to which the excavator bucket or scoop capacity is utilised or the utilisation of the capacity of dump trucks used in open pit mines [8].

With respect to underground machinery (eg shaft hoists or main belt conveyors), which work "in one setting" under stable conditions, have performance indicators adapted to their conditions [14]. It must be noted that the definition the author uses for the term OEE indicator with relation to shaft lifts, differs from that used in the manufacturing industry.

A number of relevant measurements have been used in the past in Polish underground coal mining, where the mechanised, longwall mining system dominates. These have been described in the past [15], and include:

- the continuity of mining / mining rate (the ratio of mining time to longwall shearer/cutter’s work on the wall),
- longwall shearer speed utilisation ratio (ratio of average cutting speed to maximum, nominal cutting speed of longwall shearer/cutter),
- indicator of the uniformity of the operation of the longwall shearer (the ratio of the minimum time of one extraction to the maximum time of one extraction),
- the utilisation of the longwall shearer in a 24-hour period (the ratio of minutes worked in terms of mining / loading of waste, to a 24-hour period expressed in minutes -1440),
- the number of minutes of failure per 1000Mg of mining (so-called breakdown rate) in daily, monthly, quarterly and annual periods,
- performance index of production of mining shifts (the ratio of the time of availability of shifts minus the duration of unplanned breaks not provided for in terms of availability, expressed in %).

In the past, calculation of these indicators was abandoned because of the manual, labor-intensive methods necessary to measuring some of them. Nowadays it is possible to calculate them automatically, i.e. in the systems of monitoring processes and equipment offered by FAMUR S.A. (E-mine), Elgór-Hansen (eg Mine-view) or other manufacturers.

Today, for the needs of its clients FAMUR S.A. offers and delivers to its customers - users reports on the effectiveness of the mining machines with the time structure shown below, within the E-mine system.

![Figure 8. Structure of utilisation of continuous miner as reported within the FAMUR S.A. E-mine system.](image-url)
The presented model illustrates information available in the E-mine system with regards to the loads of the electrical motors on the longwall shearer and of the speed with which it moved, as well as the various time definitions that were adopted. Also, at the request of one of the clients, the utilisation of the working time was also shown (according to [6, 15]).

Other possibilities are still being sought to identify and apply more effective measures in assessing the efficiency of mining machinery management. At present, among other things, the ratio of workers (pit or total) to one unit of production, eg using the long wall, as the measure of the efficiency of the whole mine process system (not just the basic process).

6. OEE indicator in assessing the efficiency of machinery used in the coal mining

Manufacturing processes in a properly designed production system are organised within the necessary space, which does not limit or inhibit the process. The processes for enrichment or purification processes, which may only sometimes form part of the operational processes in coal production, are in some ways similar to manufacturing processes. Therefore, it would theoretically seem possible to use the OEE to evaluate the use of processing equipment. However, the technological characteristics of mineral enrichment processes and the processing properties of technical systems make the index of equipment utilisation not fully consistent with the definition of OEE.

Mine extraction processes are much more influenced by natural factors and the resulting constraints. There is also a spatial limitation resulting from the characteristics of the deposit, the selection area or the technical and economic range of the machinery and equipment (eg the margin of profitability of transport by means of tyred vehicles or the length of the power cord). This introduces a different working time structure similar to intermittent transport. Changes resulting from speed restrictions, direction changes, or stopping machine (‘red light’).

While in machine production processes quality assessment is performed in quality control processes (including in-process and final quality) as well as in terms of customer complaints based on relatively easy to define indicators, defining quality in the mining process (including extraction and transport operations), is more difficult. Taking into account typical quality parameters in mining (eg ore crushing or the quality of raw coal), only to a certain extent do they depend solely on the working conditions of the available equipment. In the coal-bed wall system, the layer of false roof caving into the excavation can change its thickness by influencing the variable assessing the quality of the output. The increase in thickness of the deck beyond the technical capabilities of the applied technical system causes the loss of minerals, which in the mining industry is also part of the quality of the process. Also, the adoption of a quality measurement standard (eg ore crushing or calorific value / carbon calorific value) is not consistent with the OEE indicator.

Defining sub-indices (availability, use, quality) other than the OEE method described will result in a different quality indicator that is not comparable to OEE known from the manufacturing process. Emphasising that the OEE is only one of the KPIs and as such may be taken as a starting point for developing a new performance index covering the specific nature of the processes of hard coal mining.

7. Summary - the OEE indicator and hard coal mining processes

The basic criterion for the effectiveness of the production process is the economic result. Therefore, the search for ways to improve this result must cover all areas, and in fact, all the processes performed within the enterprise. To this end, diagnostic tools that are appropriate for the system of processes being investigated and the conditions of the system’s implementation are necessary. These indicators should also allow for the comparison of the efficiency of similar processes in different manners (using different technical systems) under comparable conditions. Therefore, the OEE indicator for a relatively homogeneous group of production processes is a functional tool.

When analysing the effectiveness of using OEE indicators in hard coal mining, the following recommendations may be formulated:
• The application of diagnostic tools, methods and measurement of performance parameters, is necessary.
• The adaptation of existing industrial process diagnostics tools of one kind to another may prove pointless.
• The adaptation of existing tools and methods of diagnosing processes of one kind to another industrial type cannot consist of tailoring the process to these tools.
• The selection and application of methods and tools of process diagnosis requires knowledge of the structure of these processes and the sociotechnical systems implementing these processes.
• The OEE indicator in its definition and design is not suitable for assessing the efficiency of equipment used in the extraction process.
• Defining sub-indices (availability, use, quality) other than the OEE Indicator described will result in a different quality indicator that is not comparable to OEE as known from production processes.
• It seems appropriate to revisit the KPI indicators known and applied in the Polish mining industry in the past.

The comments presented are reflections and aim to contribute to a discussion, which is without a doubt necessary, in order to develop effective and relatively simple indicators for the assessment of coal mining process efficiency.

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