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MODEL OF ECO-EFFICIENCY ASSESSMENT OF MINING PRODUCTION PROCESSES

MODEL OCENY EKOEFEKTYWNOŚCI PROCESÓW PRODUKCJI GÓRNICZEJ

The paper presents an author's method of eco-efficiency assessment of mining production processes in hard coal mines, which enables integrating results of evaluating both environmental and economic aspects. The proposed method uses life cycle approach to assess environmental efficiency and the result of operating activities to assess economic efficiency. The comprehensive method of assessing mining production processes was proposed as the Key Performance Indicator (KPI) in hard coal mines in Poland to be used to support decision making in mining companies.

Keywords: eco-efficiency, life cycle assessment, result of operating activities, hard coal mine

W artykule przedstawiono autorską metodę oceny efektywności procesów produkcji górnictwa w kopalniach węgla kamiennego, która umożliwia zintegrowanie wyników oceny aspektów środowiskowych i ekonomicznych. Proponowana metoda oceny wykorzystuje podejście cyklu życia do oceny efektywności środowiskowej oraz wynik z działalności operacyjnej do oceny efektywności ekonomicznej. Opracowaną kompleksową metodę oceny procesów produkcji górnictwa zaproponowano jako kluczowy wskaźnik efektywności KPI (*Key Performance Indicator*) kopalń węgla kamiennego w Polsce stosowany do wspomagania procesów decyzyjnych w przedsiębiorstwach górnictwa.

Słowa kluczowe: efektywność, ocena cyklu życia, wynik z działalności operacyjnej, kopalnia węgla kamiennego

1. Introduction

Mining activity is a complex process which has a significant impact on the environment. Most of the papers presented in the literature on the efficiency of hard coal mines concentrate on economic aspects, while research focused on the influence of mining on the environment is

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approached separately. Basing on the literature review it was concluded that there are no methods which would enable performing a complex assessment of environmental and economic efficiency of mining production processes. Taking into consideration the importance of innovative works associated with coal production and use, as well as minimizing environmental impacts of hard coal mining, as at present hard coal mining is the foundation of energy production in Poland, a multi-aspect assessment of the processes is crucial. That is why, the paper presents a complex method of eco-efficiency assessing of mining production processes in hard coal mines. The method enables integrating results of assessment of both environmental and economic aspects.

The basic purpose of the paper is to present a method of eco-efficiency assessment of production processes in hard coal mines. The proposed method can be applied to support decision making associated with multivariant assessment of operational and investment processes in a coal mine, and facilitate selection of a variant of coal production which is best economically justified and has the lowest impact on the natural environment. Nowadays there are no such models for hard coal mines.

2. Literature review on efficiency analysis of mining production processes

2.1. Eco-efficiency assessment

Eco-efficiency was defined for the first time in 1992 by *The World Business Council for Sustainable Development* (WBCSD), as providing competitively priced goods and services, satisfying human needs and improving quality of their life, at the same time reducing environmental impact and use of natural resources, throughout their life cycle. The method of eco-efficiency was standardised for the first time in 2012 in accordance with standard ISO 14045:2012 “Environmental management – Eco-efficiency assessment of product systems – Principles, requirements and guidelines”. The standard specifies rules, requirements and guidelines concerning eco-efficiency assessment of product systems including such elements as: purpose and range of the definition of eco-efficiency assessment, environmental assessment, evaluation of a product system, quantification of eco-efficiency, interpretation, reporting and a critical review of eco-efficiency assessment.

Eco-efficiency is an indicator of innovativeness, on its basis it is possible to determine how a particular technology or product affects the environment, as well as, what their efficiency is when compared with other technologies/products. An eco-efficiency analysis enables choosing a solution bringing maximal benefit at the lowest cost and the lowest environmental burden (eco-efficient solutions). An eco-efficiency analysis is indicator of economic and environmental efficiency. The main purpose of eco-efficiency assessment of a technology is a comparative analysis of a production system, considering economic aspects (expressed as the value of a production system) and environmental aspects (expressed as environmental efficiency of a production system). Eco-efficiency is a tool of environmental management used in environmental efficiency evaluation of a production system related to its value. According to the guidelines of standard ISO 14045:2012, eco-efficiency analyses should not deal only with a technological process itself but rather consider the whole chain of technologies, considered as a collection of

unit processes and flows that model its life cycle. The method of eco-efficiency assessment is used particularly to (Hupples, 2005):

- reduce use of resources – especially use of energy, materials, water, land,
- reduce negative influence on the environment – reduce dust and gas emission, amount of produced waste, sewage and toxic substances,
- increase in the value added of the product – which means more benefits for customers resulting from improved functionality, durability and flexibility of products at lower consumption of materials and energy,
- increase in economic efficiency of production while reducing environmental impact.

The method of eco-efficiency assessment consists of the following stages:

- determining purpose and scope of an analysis – determining boundaries of a system, function of technology, functional unit, determining assumptions and limitations,
- assessment of environmental efficiency of a production system, as a component of an analysis of eco-efficiency. In accordance with standard ISO 14045:2012, life cycle assessment (LCA) technique was selected for conducting analyses of environmental efficiency,
- assessment of the value of a production system considering its life cycle perspective, as a component of an eco-efficiency analysis. In standard ISO 14045:2012 no method or technique to assess the value of a production system is mentioned,
- calculating relative indicator of eco-efficiency,
- interpretation of results of analyses.

2.2. Assessment of environmental and economic efficiency of mining production processes – previous research in Poland and around the world

Companies of various industries show more and more interest in eco-efficiency analyses. Based on the literature review it was concluded that mathematical modeling tools are applied to eco-efficiency assess (Frischknecht, 2010; Charmondusit et al., 2011). Eco-efficiency assessment of various technologies has been conducted at the Central Mining Institute for years (Golak et al., 2011; Burchart-Korol et al., 2013, 2014; Czaplicka-Kolarz et al., 2010). The literature review shows lack of complex eco-efficiency analyses of hard coal mines, covering both environmental and economic aspects integrated – they are considered separately.

A significant challenge for a mining enterprise, and hard coal mines belonging to it, is identifying the major sources of pollution. The influence of mines on the environment is mainly assessed basing on mining waste storage (see Dz. U. 2008 r., No. 138 poz. 865 of 10 July 2008 – Mining Waste Act) in waste dumps and mine water management. Additionally, due to increasingly strict requirements concerning greenhouse gases emission, methane emission into the atmosphere and use of methane captured in methane degassing stations has become an important issue. Methane hazard is one of the most serious natural hazards in hard coal mines (Krause & Krzemień, 2014; Krause & Smoliński, 2013).

In the papers Czaplicka-Kolarz (2002) and Czaplicka-Kolarz et al. (2004) was proposed using a life cycle assessment (LCA) technique which enables analyses of a hard coal mine functioning throughout its life cycle. In the environmental assessment with LCA method, apart from the factors directly affecting the environment i.e. waste storage, drainage water discharge and methane

emission; also indirect influence on the environment is considered, associated with production of raw materials, materials and energy which are used in a coal mine. In the literature there have already been papers concerning the LCA and eco-efficiency of energy production technologies, where energy production technology was based on coal. up to now the stage of coal production was treated there very superficially, without further analyses of particular mining processes.

Many papers concerning the economic aspect of activities of mining companies or coal mines, most often refer to the issues associated with costs, efficiency of operations, models of financing investment activities and operating activities. They are important for functioning of every company, yet for a mining company, because of its specific nature they are particularly important. It is so, because of several aspects which are inseparably associated with mining industry (Saługa, 2009; Turek & Michalak, 2009):

- mining activity based on mineral deposits, is characterised by:
 - its determined location,
 - uncertainty concerning supply, structure and conditions of a seam,
 - non-renewability,
- conditions of operations are highly diversified, which results from the changeable geological and mining conditions of seam deposits,
- production process is not flexible, which is associated with the fact that there is no possibility of running any alternative production,
- periods of investment and operating activities (mining the deposits) are very long,
- significant capital intensity of both investment and operating activities, with a high level of fixed costs and personnel costs.

The volume and structure of production, resulting from the resources of raw materials and non-material resources (especially human resources; and property, plant and equipment), determine the amount of incurred costs and are an important factor affecting the profit made. Efficiency of mining activity is influenced by production capacity of a coal mine, labour intensity and material consumption of production, and costs of production. Production capacity (mining capacity) of a coal mine is defined as the lowest production capacity of one of its basic technology stages (mining front, ventilation, horizontal transport, vertical transport, coal preparation plant). Most often it is the production capacity of the mining front, i.e. the total production capacity of all the extraction workings.

Original costs of mining production are tightly associated with natural conditions and geological and mining conditions of the place where it is conducted. At the designing stage it is necessary to pay special attention to adjusting production capacity of technical means of production (machines and mining equipment) to the production possibilities stimulated by the natural conditions, and geological and mining conditions of the deposit (Magda, 2014).

Dehghani, Ataee-Pour (2012) presented a new approach to calculating profitability index of a coal mine. Mining companies generate their financial result basing mainly on their operating activities, that is why the operational risk plays such a significant role for them. It means probability of either incurring operating loss or not meeting the expected level of operating profit, which are shaped by income and operating expenses. Operating income depends mainly on the demand and sales price, determined by the market, whereas operating expenses depend mainly on the company. It means that an enterprise can limit its operational risk – mainly through changes in the structure and the volume of costs associated with relocation of the possessed resources (costs here are understood as an expression of measured use of resources) (Jonek-Kowalska,

2011; Sierpińska & Bąk, 2012). Turek, Michalak (2012) discussed the problems of evaluating fixed assets which were lost as a result of mine disasters.

Dubiński, Turek (2007) concluded that the development of scientific and research activities concerning hard coal mines would be focused on combating natural hazards, especially the associated hazards, improvement of methods of mining and organization, considering requirements associated with environmental protection. The factors mentioned above to some degree influence selection of mining technology, which ought to consider the full scope of safety and efficiency of production, as well as maximal reduction of negative effects of the activity on the natural environment. That is why it is important to search tools which enable comprehensive assessment of both economic and environmental efficiency of mining production processes.

3. Results

3.1. Model of eco-efficiency assessment

Development a model for eco-efficiency assessment of mining production processes required as follows:

- choosing an indicator of economic efficiency, significant from the perspective of coal mines assessment,
- development of formulas for calculating indicators of environmental efficiency assessment with the LCA technique,
- development of a computational formula of the results of an eco-efficiency analysis.

3.1.1. Indicator of economic efficiency

Return on assets (ROA) is a measure of fundamental significance for mining companies, because they generate their financial results basing mainly, or solely, on operating activities, and financial activity is just a margin. That is why it was decided that, in the paper, to perform economic analyses aimed at comparing activities of various companies (without considering the volume of their tax burden, extraordinary profits and losses, and the degree and costs of using by them so-called financial leverages) the best indicator would be Earnings Before deducting Interest and Taxes (EBIT) commonly used in financial analyses. EBIT is calculated in enterprises within the framework of economic and financial analyses.

3.1.2. Development of the formulas to calculate indicators of environmental efficiency assessment with the LCA technique

The paper proposes a novel approach to assessment of environmental aspects applying a life cycle study, which enables assessing both the factors affecting the environment directly (i.e. waste storage, drainage water discharge, methane emission), and indirectly, which are associated with the production of basic materials and energy used in a coal mine. It is done with the life cycle assessment (LCA) technique presented in the paper. One of its main assumptions is the attempt to present all the factors associated with a given technology which have a potential influence on the environment. The LCA technique, as a component of eco-efficiency, enables assessing

a technology/ a product, among others, basing on the following environmental indicators:

- influence on human health, ecosystem quality, use of resources,
- greenhouse gases emission,
- cumulative energy demand,
- fossil fuels depletion.

LCA technique application gives an opportunity to find an answer to a question which elements of a technology (unit processes, input and output data) generate the highest environmental indicators, and thus, have the largest influence on the result of environmental assessment of the whole technology.

Based on the results of the research which we conducted to calculate the indicator of environmental efficiency, we propose, as a component of eco-efficiency assessment indicator, simplified environmental LCA of a hard coal mine expressed with formula (1), and environmental LCA of a unit process in a coal mine, expressed with the computational formula (2):

$$LCA = \sum_{i=1}^n LCA_i \quad (1)$$

where:

- LCA — life cycle assessment of a hard coal mine,
- LCA_i — life cycle assessment of a unit process in a coal mine,
- i — index of a unit process,
- n — number of all unit processes in an analysed coal mine.

$$LCA_i = \sum_{j=1}^k (r_j \cdot eco_j) \quad (2)$$

where:

- LCA_i — life cycle assessment of a unit process in a coal mine,
- r_j — amount of raw materials used (energy, water, materials etc.),
- eco_j — ecopoint for a given raw material in eco-invent database,
- j — raw material used in a unit process,
- k — amount of all commodities used in a given unit process.

A life cycle assessment enables including, apart from three main environmental aspects of hard coal mines, i.e.: methane emission, waste storage, drainage water discharge; also other input and output elements inventoried in coal mines. Sample input elements are presented in Figure 1. It also shows the main categories of influence affected by the above mentioned input and output elements. Production processes of the elements, in spite of the fact that they occur outside the mining area, are included in the life cycle of a coal mine and significantly impact on the environment. Considering environmental burden in the life cycle of a coal mine gives us a possibility to reduce it, e.g. through rational material and energy management, and appropriate selection of materials used i.e. selection of materials of lower environmental impact.

3.1.3. Development of the calculation formula of eco-efficiency analysis

The method of eco-efficiency assessment which is developed in this paper is a function of two indicators – environmental one (LCA) and economic one (EBIT). Authors also proposed

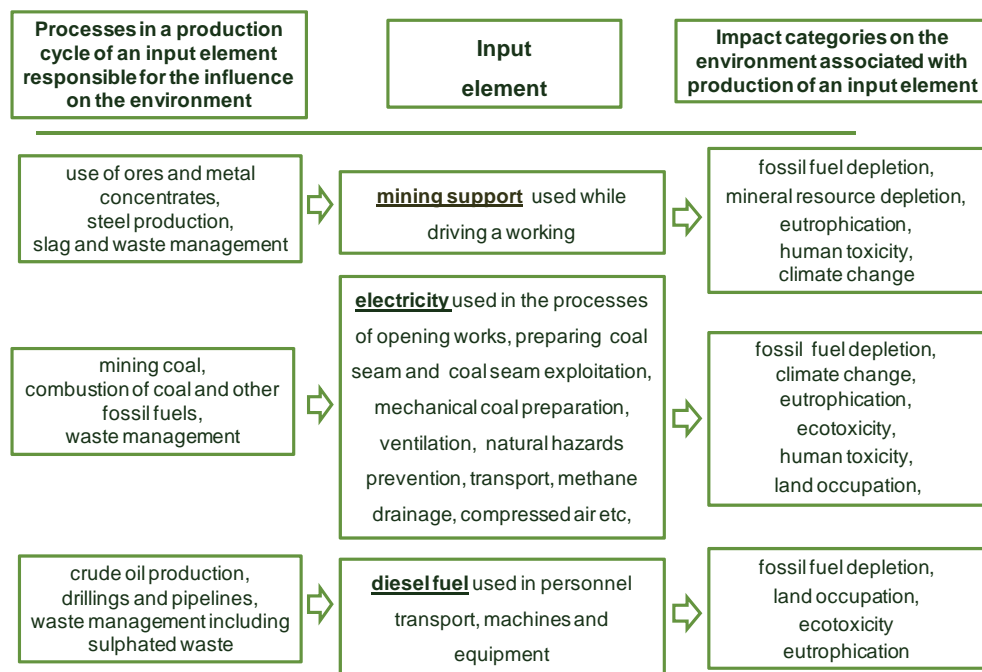


Fig. 1. Selected input elements of a hard coal mine and impact categories on the environment associated with them

Source: According to (Śliwińska & Burchart-Korol, 2014)

a method which enables compare analysis of eco-efficiency of coal mines, as well as environmental efficiency assessment of particular processes of mining production. For calculations it was developed and used a computational formula (3):

$$EE = \frac{EBIT}{LCA} \quad (3)$$

where:

- EE — eco-efficiency indicator of an analysed coal mine,
- $EBIT$ — earnings before interest and taxes of a given coal mine,
- LCA — environmental life cycle assessment of a coal mine.

The presented dependence shows that eco-efficiency is directly proportional to the EBIT and inversely proportional to the results of LCA:

**The more eco-efficient coal mine / process is,
the higher value of EE indicator is.**

Authors propose expressing eco-efficiency of hard coal mines in relative units for comparison purposes. Relative values (RV) of eco-efficiency of coal mines / mining production processes are recommended to be calculated with the formula (4):

$$RV_i = \frac{EE_i \cdot n}{\sum_{i=1}^n EE_i} \tag{4}$$

where:

- RV — relative value,
- EE_i — eco-efficiency indicator for any coal mine,
- n — number of coal mines in the analysed set,

$\sum_i^n EE_i$ — a total of indicators of eco-efficiency of coal mines in the analysed set.

The obtained relative values of eco-efficiency indicator enable ranking and comparing the analysed coal mines and their processes.

3.2. Calculation of eco-efficiency for selected coal mines. Case study

Environmental efficiency was calculated with the *LCA* technique, economic efficiency with *EBIT*, and eco-efficiency according to formula (3). Table 1 shows relative values of the obtained results: life cycle assessment – LCA_{RV} , operating profit indicator – $EBIT_{RV}$ and eco-efficiency indicator – EFE_{RV} , for six selected hard coal mines.

The best method to present results of eco-efficiency calculations is a graphic form (*eco-efficiency portfolio*). Figure 2 shows graphic interpretation of the results of eco-efficiency which were obtained with *LCA* and *EBIT*.

TABLE 1

Relative results of eco-efficiency analyses for sample coal mines

Specification	$EBIT_{RV}$	LCA_{RV}	EFE_{RV}
Coal mine 1	1.206	1.148	1.050
Coal mine 2	0.821	0.399	2.055
Coal mine 3	0.794	1.820	0.436
Coal mine 4	1.587	0.303	5.233
Coal mine 5	1.022	1.286	0.794
Coal mine 6	0.570	1.043	0.546

The graphic form of presenting results enables a quick assessment of eco-efficiency, basing on the coordinates of the point representing each coal mine in relation to the diagonal line in the graph. The higher value of *EBIT* and lower indicator of influence on the environment, calculated with the *LCA* are, the higher eco-efficiency of a coal mine is. According to the results presented in Figure 2 it was concluded that the coal mines located in Part 4 of the graph are the least eco-effective, while in Part 1 the coal mines are the most eco-effective. For coal mine 3, low eco-efficiency is associated, most of all, with the highest indicator of the life cycle assessment and a relatively low indicator of *EBIT*, when compared with other coal mines in the group of the assessed coal mines.

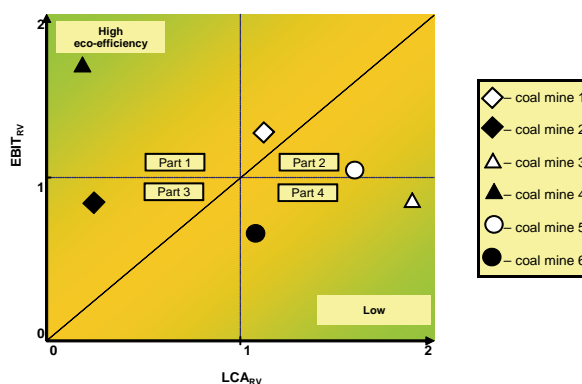


Fig. 2. Graphic presentation of eco-efficiency results (eco-efficiency portfolio) of evaluated coal mines.

Source: own analysis

4. Conclusions

The paper shows assessment method of coal mines which considers one of the essential indicators of economic assessment of coal mine operations – *EBIT* as well as environmental aspects of particular processes and the whole coal mine considering life cycle approach.

The proposed method enables conducting assessments of: environmental efficiency, economic efficiency, and eco-efficiency, both for specific processes and for a whole coal mine.

Development method of eco-efficiency assessment as a function of *EBIT* and *LCA*, links the basic purpose of operating of hard coal mines, i.e. effective hard coal production, with an environmental approach considering the life cycle. The author's method enables a comparative analysis of coal mines and ranking their eco-efficiency, including assessment of particular processes of coal production. Application of the proposed method is useful in comprehensive evaluation of hard coal mines. The method of eco-efficiency assessment can be used for the management of coal companies to support making decisions associated with analyses and assessment of various aspects of operation of subordinate coal mines, as well as conducting strategic analyses of multi-aspect efficiency of Polish mining industry.

Eco-efficiency is associated with the crucial issues concerning activities of mining companies. That is why it is proposed to consider use of the development methodology in the strategic management of mining companies, and in complex assessment of mining production processes.

Development method of assessing eco-efficiency, as a function of *EBIT* and *LCA*, can be also used to evaluate mines producing other minerals. To do so, it is necessary to identify all the unit processes in such a mine, and specify their input and output elements.

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