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ORIGINAL PAPER

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DEVELOPMENT OF SUSTAINABILITY ASSESSMENT METHOD OF COAL MINES

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ABSTRACT

Purpose	This paper presents an algorithm developed to assess all aspects of sustainable development for hard coal mines. Additionally, an algorithm to assess the environmental efficiency and cost efficiency of mining production processes was presented.
Methods	To develop the computation algorithm, detailed models were proposed for environmental assessments using Life Cycle Assessment (LCA), whereas Cost-Benefit Analysis (CBA) was proposed for economic and social assessments.
Results	The algorithm developed is used when preparing a ranking of hard coal mines which considers the main aspects of sustainable development – environmental, economic and social. The tool also enables the performance of both environmental and cost assessment for particular unit processes of mining production.
Practical implications	The practical purpose is to devise an algorithm that will perform both partial and aggregated assessment of all aspects of the sustainable development of coal mines in Poland.
Originality/value	It is the first method which includes all aspects of sustainable development and considers the process approach to assess coal mines.

Keywords

sustainability, hard coal mine, Life Cycle Assessment, Cost-Benefit Analysis

1. INTRODUCTION

Hard coal mining is the foundation of Poland's economic development. Coal plays a key role in providing Poland's energy safety. In the forecast of the demand for fuel and energy it is predicted that, in the near future, there will be no significant changes in the structure of raw materials used to produce electricity in Poland. According to Poland's Energy Policy 2050, coal will remain the main source of energy. Poland is one of the ten biggest producers of coal in the world (Table 1).

Table 1. Main producers of coal, 2012 (IEA, n.d.)

Producers	Mt	% of world total
People's Republic of China	3 549	45.3
United States	935	11.9
India	595	7.6
Indonesia	443	5.7
Australia	421	5.4
Russian Federation	354	4.5
South Africa	259	3.3
Germany	197	2.5
Poland	144	1.8
Kazakhstan	126	1.6
Rest of the world	808	10.4
World	7 831	100.0

The main aim of this paper is to develop an algorithm that will assess all aspects of sustainable development for hard coal mines and the environmental and cost efficiency of mining production processes.

2. SUSTAINABLE DEVELOPMENT IN COAL MINES

2.1. Assessment of sustainable development – state-of-the-art

In 1987 the World Commission on Environment and Development (Brundtland Report, 1987) at the United Nations (UN) defined sustainable development (SD) as *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. UNEP's Life Cycle Initiative in cooperation with the Society of Environmental Toxicology and Chemistry (SETAC) promotes Life Cycle Management (LCM) as an indicator of sustainable development, through combining the environmental assessment of a life cycle, the social assessment of a life cycle and the costs of a life cycle (UNEP/SETAC, n.d.). Burchart-Korol presented in the paper (2011) a review of complex assessment methods of sustainable development and a potential application of Life Cycle Sustainability Assessment (LCSA) and Socio-Eco-Efficiency

Analysis (SEEBalance). Applying Life Cycle Perspective (LCP) to the three basic pillars of sustainable development enables the incorporation of the issue of sustainable development in the decision making process. LCP means considering the aspects (environmental, economic and social) associated with the product throughout its life cycle (from extracting raw materials, through to processing materials, production, distribution, exploitation, repairs and maintenance, utilization and recycling) and in the value chain.

Indicators of sustainable development are basic monitoring tools, which enable the visualisation of the very essence of the concept in a measurable form. In recent years the importance of sustainable development has been steadily growing, especially when considering environmental issues associated with climate warming. As a result of the global effects of environmental problems, increasing ecological awareness, as well as more and more restrictive and complex environment protection legislation, the conditions of operating business activities changes too – especially in the power industry sector. That is why in the following years it will be more and more necessary to take actions aimed at reducing the emission of greenhouse gases, which result from the present problems of global climate changes. Czaplicka-Kolarz, Krawczyk, and Burchart-Korol (2013) identified factors of underground coal gasification influencing balanced Life Cycle Assessment, and they also attempted to assess the influence of implementing underground coal gasification technology on the indicators of sustainable development in Poland.

2.2. The importance of sustainable development aspects in hard coal mines

Issues of sustainable development are also reflected in strategies and action plans of the hard coal mining industry, and these issues play an important role in setting aims and priorities associated with the long-term development of Poland and its ability to follow the rules of sustainable development.

As Poland implements the European Union regulations concerning issues of environmental protection, coal mines ought to meet conditions concerning using the environment which are specified in relevant decisions and administrative permits. Environmental protection is a European Union priority. That is why such an important issue for coal mines is following the requirements associated with coal production. As far as environmental protection is concerned, one of the priorities in the strategy of coal mines is obtaining specific volumes of hard coal production whilst having a minimal negative impact on the environment. The aim of the Polish state's policy towards the hard coal mining industry is the rational and effective management of coal deposits located in the territory of the Republic of Poland, so that the deposits serve the generations to come.

Mining activity is associated with negative influence on the environment (Bednorz, 2011). Preventing significant environmental impact is becoming more and more important for coal mines. Coal mines implement Environmental Management Systems and develop environmental protection strategies. The main environmental aspects of coal mines in Poland are: mine waters, mining waste and methane emission

into the atmosphere, thus the priorities for environmental protection are:

- preventing the generation of waste other than those from mining, including hazardous waste,
- limiting the amount of mining waste, through the better management of waste on the surface and in underground workings,
- expanding the scope of reclamation and better management of mining waste heaps and other areas degraded by mining activity – restoring the utility value of degraded areas,
- minimizing the influence of mining activities on the surface by operating mining activities in a way that limits deformation of the surface and through wider use of prevention measures,
- decreasing the impact of waste water, especially water with abnormal salinity from dewatering coal mines, on surface water,
- decreasing the emission of dust and gas pollution into the atmosphere, especially reducing the emission of greenhouse gases,
- limiting the use of energy,
- the efficient collection of methane released from the rockmass to minimize its emission into the atmosphere, as well as preventing methane hazards underground to provide safe working conditions,
- to continuously increase the economic use of methane drained and brought to the surface,
- reducing noise emission into the environment.

Some examples of the application of life cycle assessment in the mining industry can be found in the literature (Durućan, Korre, & Munoz-Melendez, 2006; Awuah-Offei & Adekpedjou, 2011). Work associated with the environmental assessment and economic assessment of mining investments has been conducted for many years both in Poland and around the world. It was concluded that the work associated with assessing the efficiency of coal mines refers to separate issues, these being: economic, environmental and social, without providing a common approach which would enable the assessment of all the aspects of sustainable development. It has also been concluded that at present there are no complex analyses concerning the application of costs and benefits analysis methodology which would also consider non-financial costs and the benefits of running mining activities in Poland. Krawczyk, Majer, and Krzemień (2014) presented the possibilities of applying costs and benefits analysis to calculate the eco-efficiency of coal mines in Poland. Mishra, Sugla, and Singha (2013) presented factors which influence the productivity of coal mines. Sali (2011) presented methods of economic assessment of a coal mine which are used in Ukraine. The aforementioned methods employ such indicators as: economic attractiveness and economic credibility, which are an aspect of the technical conditions, geological and mining conditions, organizational conditions and economic conditions of coal mines.

Based on the literature review it was concluded that hitherto works concerning the efficiency of coal mines (including environmental, economic and social efficiency) do not consider the process approach.

3. RESULTS AND DISCUSSION

In the paper a developed algorithm for assessing both indicators of sustainable development of hard coal mines and environmental and cost efficiency of mining production processes is presented. It was one of the main aims of the project titled “Development of an expert system to assess environmental, economic and social efficiency of coal mines in Poland”, financed by the National Centre for Research and Development within the framework of the Applied Research Program.

Within the framework of the research two modules of coal mine assessment were developed. The first enables a complex assessment of coal mines, considering all the aspects of sustainable development – environmental, economic and environmental. The second refers to the assessment of environmental efficiency and cost efficiency for particular processes of mining production.

3.1. An algorithm to assess the sustainable development of coal mines

Figure 1 presents an algorithm of assessment of all aspects of sustainable development for coal mines (module I).

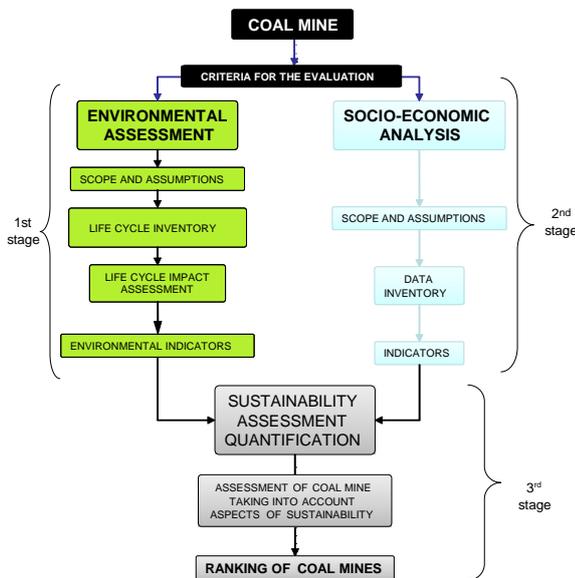


Fig. 1. The methodology framework of the algorithm for the development of sustainability evaluation, proposed by the authors (source: own analysis)

The structure of the algorithm to calculate indicator of sustainable development of coal mines (module I) consists of three stages:

1. environmental assessment,
2. socio-economic analysis,
3. sustainability assessment quantification of coal mines.

Stage 1. The environmental assessment of coal mines

Life Cycle Assessment (LCA) was selected to perform the environmental assessment of coal mines. The choice of this technique is justified because environmental assessment performed with LCA, excluding the factors which affect the environment directly in case of a coal mine, i.e. mine waste storage, discharging mine water, and methane emission, also considers the indirect influence on the environment associated with producing raw materials, materials and energy used

by a coal mine. Thanks to such an approach it is possible to identify the impact which is both directly and indirectly associated with the functioning of a coal mine. The environmental assessment of Life Cycle Assessment is used in assessing environmental aspects associated with a product throughout its whole life cycle. Śliwińska and Burchart-Korol (2014) presented the benefits of using Life Cycle Assessment (LCA) for the environmental analysis of a hard coal mine.

Following the standard ISO 14040:2006, LCA is conducted in four stages:

- determination of an aim and scope of the analysis,
- collection and analysis of input and output data,
- environmental impact assessment according to specified categories,
- interpretation of results.

The application of LCA enables several environmental indicators to be obtained. ReCiPe 2008, the most complex method of environmental assessment, enables the assessment of damage in three categories: human health, ecosystems and resources, as well as assessing influence in 18 categories of environmental impact:

- climate change,
- ozone depletion,
- terrestrial acidification,
- freshwater eutrophication,
- marine eutrophication,
- photochemical oxidant formation,
- particulate matter formation,
- human toxicity,
- terrestrial ecotoxicity,
- marine ecotoxicity,
- freshwater ecotoxicity,
- ionising radiation,
- agricultural land occupation,
- urban land occupation,
- natural land transformation,
- water depletion,
- mineral resource depletion,
- fossil depletion.

The methodology of coal mine environmental assessment was expressed with the following computation formula (1):

$$Eco = \sum_{j=1}^k (r_j E_j) \quad (1)$$

where:

Eco – the indicator of environmental efficiency calculated for a coal mine with LCA,

j – the raw material used in the coal mine,

k – the amount of all raw materials used in the coal mine,

r_j – the amount of raw material used in the coal mine (energy, water, materials etc.),

E_j – ecoindex for the raw material (ecoinvent 3 database).

Stage 2. The socio-economic analysis of coal mines

For the socio-economic analysis of coal mines, the Cost-Benefit Analysis (CBA) method was proposed. It is a method of comparing and assessing all the costs and benefits for society and ecosystems, associated with a particular activity and considering both its tangible and intangible costs and

benefits. Thanks to the use of the CBA method it is possible to assess the contribution of hard coal mining to the increase in the economic welfare of the region, and the country. The developed algorithm enables assessments to be made from the perspective of the population's interest (of a region and a country), whereas financial analysis only assumes the owner of the coal mine's perspective.

Computation methodology for socio-economic analysis of a coal mine consists of the following stages (European Commission, 2008):

- adjusting the effects of taxes, subsidies or other transfers,
- adjusting external effects,
- transforming market prices into accounting prices, which enables the consideration of social costs and benefits (establishing conversion factors).

An updated economic net present value (*ENPV*) was proposed as a result of CBA analysis. The letter "E" which precedes the markings of the indices informs that they do refer to economic analysis (Kawala, 2002; European Commission, 2008). Based on the work of Krawczyk et al. (2014) the developed index *ENPV* was selected for coal mines according to the following formula (2) (European Commission, 2008):

$$ENPV = \sum_{t=0}^n a_t S_t^E = \frac{S_0^E}{(1+r)^0} + \frac{S_1^E}{(1+r)^1} + \dots + \frac{S_n^E}{(1+r)^n} \quad (2)$$

where:

ENPV – result of the socio-economic analysis of a coal mine (economic net present value),

S_t^E – balance of the flow of costs and benefits generated by a coal mine in the given years of the analysed reference period,

n – reference period in years (analysed period),

a_t – economic discount rate which equals: $a_t = \frac{1}{(1+r)^t}$,

r – economic rate of return,

t = 0, 1, 2, ..., *n* – the year of the calculation period.

There are papers concerning the social reception of mining activities which indicate that in the balance of external costs and benefits generated by a coal mine it is necessary to consider the following costs (Krawczyk et al., 2014; Kaszowska & Nowak, 2013; Martyka, Nowak, & Tausz, 2001; Sobczyk, 2007):

- costs of work related accidents,
- costs of occupational diseases,
- costs of mining damage and loss of areas degraded by mining activity (decrease in utility and aesthetic value of an area),
- environmental costs caused by pollution emission (especially unmanaged mining waste, saline mine water, methane),
- benefits of newly created work places,
- benefits of cooperation between coal mines and other business entities,
- local area benefits from tax revenue.

Stage 3. The assessment of aspects of sustainable development for coal mines

To calculate the indicator of sustainable development assessment a computation formula which combines the

results of the socio-economic and environmental analysis referring to the analysed period of coal mine activity is proposed. The devised equation (3) is as follows:

$$SD = \frac{ENPV}{Eco} \quad (3)$$

where:

SD – the indicator of sustainable development,

ENPV – result of the social and economic analysis of a coal mine,

Eco – the indicator of environmental efficiency calculated for a coal mine with LCA.

The indicator of sustainable development enables the comparison of coal mines. The proposed method of calculating the indicator of sustainable development is based on using both LCA and CBA simultaneously. This is why it is necessary to pay special attention to the inclusion of all the environmental aspects in the analysis. The European Commission's guidelines concerning the methodology of CBA analyses show that the total impact of investment or business activities on the environment is often impossible to express in terms of money, and impossible to consider in CBA (European Commission, 2008). There is a similar situation with LCA. To avoid the mistakes associated with considering the same errors in both LCA and CBA, external effects (mainly environmental ones) are verified during CBA to check whether they are also listed in a given category of the environmental impact in the Life Cycle Impact Assessment (LCIA). Only the environmental aspects which do not appear in LCA ought to be considered in CBA (Krawczyk et al., 2014).

The proposed algorithm of assessing sustainable development enables the complex assessment of coal mines considering socio-eco-environmental aspects to be performed. To perform the assessment of mining production processes another module, enabling environmental and cost assessment of particular processes, was developed (Fig. 2).

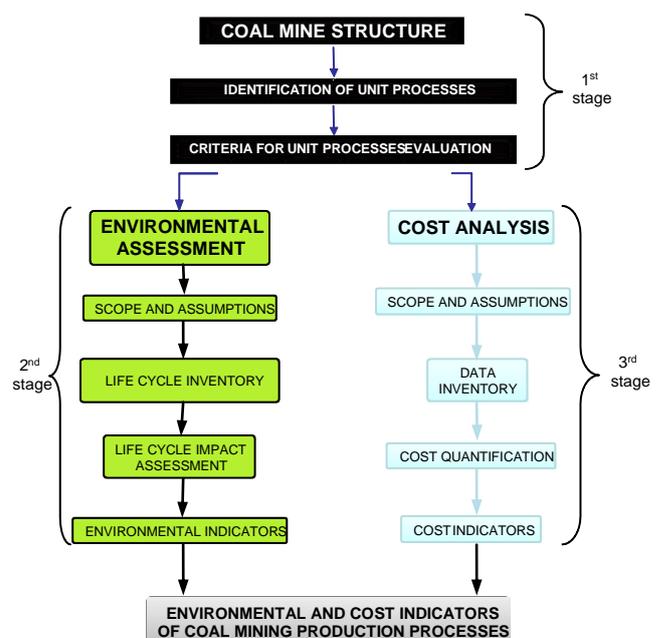


Fig. 2. The methodology framework of an algorithm for the development of the environmental and cost assessment of unit processes in a coal mine, proposed by the authors (source: own analysis)

3.2. An algorithm of assessing environmental and cost efficiency of unit processes in mining production

The second assessment module enables the environmental and cost assessment of given coal mine processes referred to a functional unit, expressed as 1 MJ of chemical energy contained in coal (thus also considering quality of coal) to be performed.

The structure of the computation algorithm applied to develop a model of assessment of environmental and cost efficiency of mining production processes (module II) consists of three stages (Fig. 2):

1. the identification of the unit processes of a hard coal mine,
2. the environmental processes assessment referred to as a functional unit,
3. the cost assessment of processes referred to as a functional unit.

Stage 1. Identification of the unit processes in a hard coal mine

The structure of the hard coal production process was defined as a system of unit processes, activities and technological operations, realized at a specified time, in a specific order and specific space, conducted by personnel with the use of certain technical measures with the aim of producing commercial coal within appropriate quality parameters (Fig. 3).

The term "unit processes" refers to technological processes which have to be followed to produce hard coal:

- preparatory processes (opening and preparatory works),
- basic processes (mining and processing),
- auxiliary processes (ventilating, work safety, transport etc.),
- accompanying processes (environmental protection and repairing mining damage).

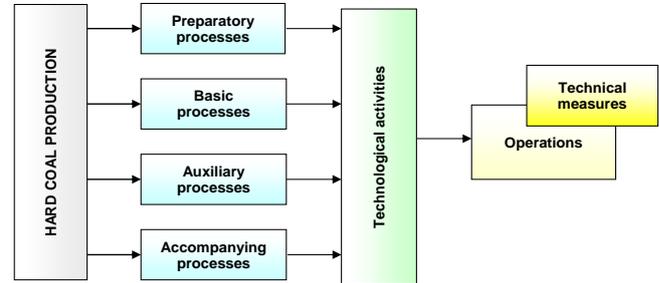


Fig. 3. Structure of the hard coal production process (Turek, 2013)

The term "operations" refers to actions aimed at achieving a particular goal (utility effect) which are realised within the framework of specific unit processes.

The operations are divided into "technological activities", i.e. actions performed in a specified place by personnel (coal mine services, departments) using technical equipment (machines, devices etc.). To characterise the course of hard coal production, analysis was carried out whilst considering the division of processes into unit processes, collected in Figure 4.

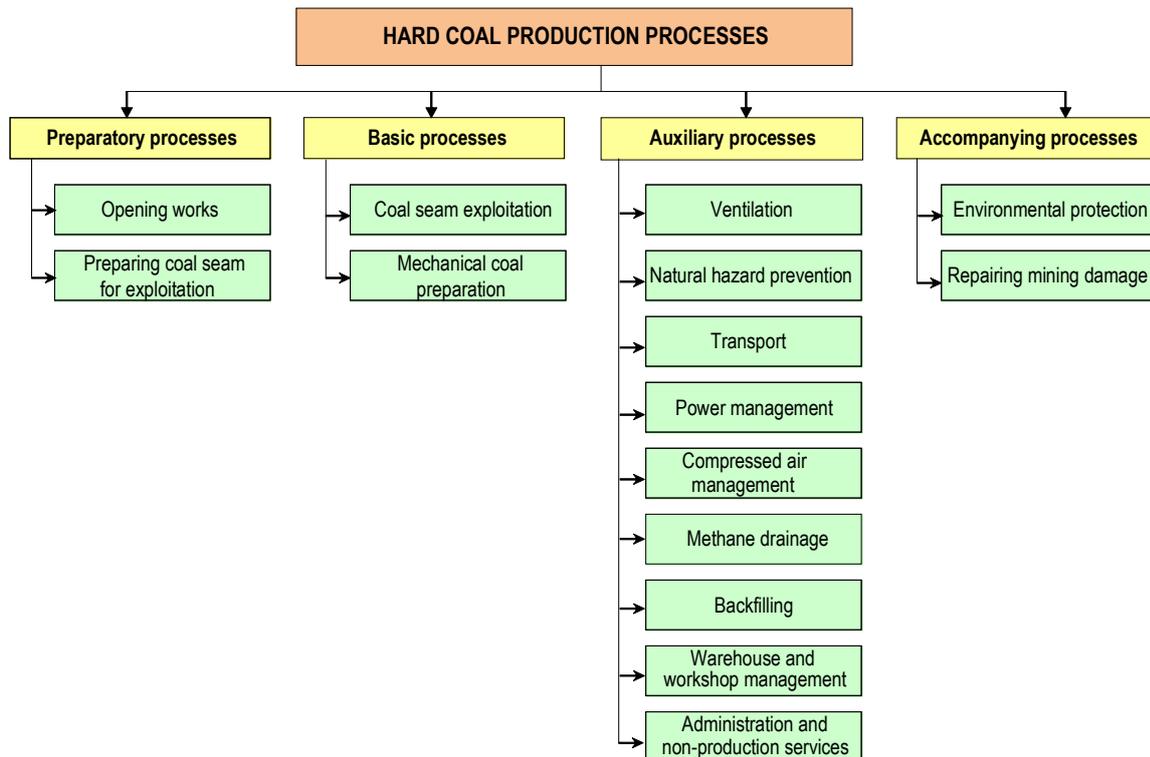


Fig. 4. Hard coal production processes (own analysis based on Turek, 2013)

Stage 2. Environmental processes assessment

The next step in the algorithm is the preparation of environmental analysis, which is when applying LCA is proposed. This enables the assessment of identified coal mine processes while considering numerous categories of envi-

ronmental impact. An important stage within the framework of LCA is identifying all the input and output elements for particular processes. Based on the analysis of all the processes of mining production, input and output elements were selected, which:

- can occur in particular processes,
- are measurable or at least possible to assess with high probability.

They are collected in Table 2.

Table 2. Main input and output elements of the coal production process

Processes in hard coal production	Unit process	Input elements	Output elements
Preparatory Processes	Opening works	Electricity, air, compressed air, explosives, water, cryogenic or petrifying substances (if a shaft is driven), elements of shaft or mine working lining.	Driven shaft or working, gangue, water of natural inflow or technological processes, outlet air, noise.
	Preparing coal seam for exploitation	Electricity, air, compressed air, explosives, water, elements of mine working lining.	Driven working, gangue, run-of-mine coal, water of natural inflow or technological processes, outlet air, noise.
Basic Processes	Coal seam exploitation	Electricity, air, compressed air, water, emulsion, explosives, resins, foams, insulation materials, elements of mine working lining, timber.	Run-of-mine coal, gangue, water of natural inflow or technological processes, outlet air, noise.
	Mechanical coal preparation	Run-of-mine coal, water, electricity, compressed air, various chemicals, flocculants and other specific exploitation materials.	Commercial coal, coal preparation waste (stone, sludge, slime, sewage, flotation tailings), used chemicals, noise.
	Ventilating	Electricity in air.	Outlet air, noise.
	Natural hazards prevention	Electricity, compressed air, water, ash-water mixtures, ignition inhibitors, inert gases, explosives, stone dust, various chemicals.	Outlet air, methane, water natural inflow and technological processes, noise.
	Transport	Electricity, diesel fuel.	Noise.
Auxiliary Processes	Power management	Fuel – methane, gas or coal, water.	Heat energy, ashes and other waste.
	Compressed air management	Electric energy/electricity.	Compressed air and noise.
	Methane drainage	Electric energy/electricity.	Methane, noise.
	Backfilling	Water, electric energy/electricity, compressed air, various backfill materials, materials for building backfilling installation and dams.	Polluted backfill water, slime, noise.
	Workshop and warehouse management	Electricity, welding gases, oils, greases and chemicals, various exploitation materials.	Sewage, worn-out elements of machines and devices, used exploitation materials, noise.

Source: own analysis.

The environmental assessment of a coal mine unit process was expressed according to the following computation formula (4):

$$Eco_i = \frac{\sum_{j=1}^k (r_j E_j)}{W_p} \quad (4)$$

where:

Eco_i – the indicator of environmental efficiency calculated for a coal mine unit process with LCA,

r_j – the amount of used raw materials (energy, water, materials etc.),

j – the specific raw material used in a unit process,

E_j – the eco-index for a raw material (from ecoinvent 3 database),

k – the amount of all raw materials used in a unit process,

W_p – the volume of production associated with a unit process i expressed as chemical energy in the extracted coal,

i – the unit process of a hard coal mine.

As a result of the environmental assessment it is possible to obtain numerous environmental indicators for coal mine unit processes.

Stage 3. Cost assessment of processes

To perform a cost analysis it is necessary to collect direct costs concerning particular unit processes, e.g.: material input, labour, energy, external services and depreciation. The equation to calculate costs for a unit process is as follows (5):

$$K_i = (K_{m_i} + K_{r_i} + K_{e_i} + K_{u_i} + K_{a_i} + K_{p_i}) / W_{p_i} \quad (5)$$

where:

K_i – cost assessment of a process i referred to a functional unit,

i – unit process of a hard coal mine,

K_{m_i} – costs of materials,

K_{r_i} – costs of labour,

K_{e_i} – costs of energy,

K_{u_i} – costs of external services,

K_{a_i} – costs of depreciation,

K_{p_i} – other costs not included in the above cost categories,

W_{p_i} – the volume of production associated with a unit process i expressed as chemical energy in produced coal.

As a result of cost analysis it is possible to obtain the direct costs of coal mine unit processes, thus it is possible to calculate costs of unit processes, which enables a comparative analysis of mine production processes to be conducted.

4. CONCLUSIONS

The developed algorithm of sustainable development assessment can be used to support management boards of coal mining companies: firstly, in making decisions associated with analysing and assessing various aspects of the functioning of subordinate coal mines, and secondly, in strategic analyses of the multi-aspect efficiency of the Polish mining industry during simulations of changes in coal production (mainly investment plans and significant technological changes) and its influence on environmental, economic and social efficiency.

The developed method of assessing the sustainable development of coal mines can be used by decision makers to:

- assess coal mines from the perspective of those planning the strategy of development for the mining industry,
- assess the influence of hard coal mining on Poland’s sustainable development indicators,
- assess the effective management of non-renewable resources.

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