Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 4, Issue 2 / 2019, pp. 197 - 218

F. Petroleum and Mining Engineering

Received ***28 February 2019*** *Accepted* ***30 May 2019***
Received in revised form ***17 April 2019***

Responsible mining approach for sustainable development - research concept and solutions

CARSTEN DREBENSTEDT*

Technische Universität Bergakademie Freiberg, Germany

1. Introduction

In 1556 Agricola published the twelve books of mining and metallurgy. The first book has the title: The defense of mining against the attacks of the opposition and the evidence of their benefit. This shows that the conflict between the mining and metallurgical activities and the society has a long tradition.

Today the term “sustainable development” is often pointed out like the main guideline for the development of the modern society and for the mineral sector.

But the term is not new. The first time the term was used in 1713 by Hans Carl von Carlowitz, the chief mining inspector in Saxony, in his book “Silvicultura oeconomica” – about the economy of the forest. Because of the demand in wood e.g. for equipment construction, underground support, and char coal production for metallurgical processes, the demand in this material increased and strategies and measures were needed to reduce the consumption and to regulate the afforestation.

Initiated in 1972 by the Club of Rome with the report “The Limits to Growth” starts the modern discussion about the limit of economic growth because of the limited availability of natural resources, on special example of crude oil. The first oil crises in 1973 pushed the consideration of natural resources.

*Correspondence address: Carsten.Drebenstedt@mabb.tu-freiberg.de;
drebenst@mabb.tu-freiberg.de

In 1987 was published the so called Brundtland Report “Our Common Future” from the United Nations World Commission on Environment and Development (WCED). An oft-quoted definition of sustainable development is defined in the report as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Al least with the UNCED (United Nation Conference on Environment and Development) 1992 in Rio de Janeiro sustainable development was defined like a balanced development between economy, ecology and social needs.

However, the concept of sustainable development is to keep a system (economic, social or ecosystem) in function considering the well-being of future generations.

The mining industry may come in conflict with some of the above mentioned definitions. Can mining be sustainable? Yes, because mining is an inseparable part of the development of our society. The responsibility is, to improve the mining technologies permanent and develop science and technologies to avoid and minimize negative impacts to the environment and society.

2. Sustainable development goals of UNESCO

The UNESCO submitted the sustainable development goal 2030. Analyzing the goals is becomes clear, that these goals are not in contradiction to the development of the mining industry. Up to now, the knowledge about the role of mining in the society is often understand incorrect. The picture, formed over centuries is dominates by hard and dirty work, land disturbance, negative impacts to the environment and social spheres. Looking to the Sustainable Development Goals 2030 of the UNESCO it becomes clear, that mining contributes positive to these targets.

At first there are direct links to mining products, like “Clean Water and Sanitary” (target 6), “Affordable and Clean Energy” (7), “Industry, Innovation and Infrastructure” (9). Here contributes for example ceramics, aggregates or energy commodities. In addition, in other targets, like “Zero Hunger” (2) and “Good Health and Well-Being” (4) we find direct link to fertilizer in agriculture or metals and sources for radiation in hospital.

Other direct effects of mining to the society are employment, salaries, taxes and social responsibility. This correlates well with the target 8 “Decent Work and Economic Growth”. This is the basic for targets like “No Poverty” (1), “Zero Hunger” (2), “Quality Education” (4), “Gender

Equality" (5), "Reduced Inequalities" (10), "Sustainable Cities and Communities", and "Peace, Justice and Strong Institutions" (16).
The targets "Life Below Water" (14) and "Life on Land" (15) addressed to reclamation demand in mining industry, where we have today very good results in increasing biodiversity in urban areas. "Responsible Consumption and Production" (12) and Climate Action" (13) are very important issues, to which contributes mining with delivering the needed minerals for new technologies, and these are task for the mining industry by self for improvement with energy and material saving technologies, reduction of losses and waste.
The target 17 "Partnership for the Goals" invites mining industry to be a part of the solution.

3. Conventional and alternative mining approaches

The world mining industry is characterized by several challenges. The growth of population and living standard leads to an:
− Increase of Demand in Mining Products
− Increase of Prices
− Increase of Profits (Drive of Market)
− Increase of Impacts to the Environment
− Increase of Mining Waste
− Increase of Land Occupation and related conflicts
− …
Since 2004 the world mining industry develops very fast, with a growth of 2-3% per year, for several commodities faster. Nowadays the world mining production reaches more than 30 B t. In average every human being consumes 5t per year, in developed countries more than 20t per year.
Under this conditions new strategies required for covering the future raw material demand. The main directions are:
− Reducing the consumption
− Minimizing the raw material demand in products
− Use of alternative materials; material design
− Recycling (urban mining)
− Increase the recovery rates from deposits
− Exploration of new deposits
− Development of mining technologies for new deposit conditions
In the following discussed two mining approaches, the "maximum profit" driven one and the more responsible mining concept with "moderate profits". "Moderate" is a profit, when the level is attractive for investors

with high environmental and social standards. Sometimes mining projects with low standards offer high (maximum) profits.
Of cause, the moderate profit concept only works, if this approach is applied for all mining project. In reality we see and today large differences in level of mining safety and the environmental and social standards in mining projects. Plus different government regulations and subsidies this differences lead to not real free market conditions.
However, the improvement of mining industry must be happening always to keep the public acceptance.
The main strategies to improve the mining activities are:
− Increase of recovery rate
− Use of environmentally friendly technologies
− Consideration of reclamation and long term environmental effects of mining
The strategies must be realized by concrete measures. In this paper presents some results of research and development projects of the Institute of mining at Technische Universität Bergakademie Freiberg (see chapter 3).

3.1. General Mining Approach

The general mining approach is illustrated in figure 1. The concept is maximum profit driven, which can be summarized by formula 1

$$\text{(Maximum) Profit } P_G = \text{Income } I_G - \text{Direct Costs } C_{DG} \qquad (1)$$

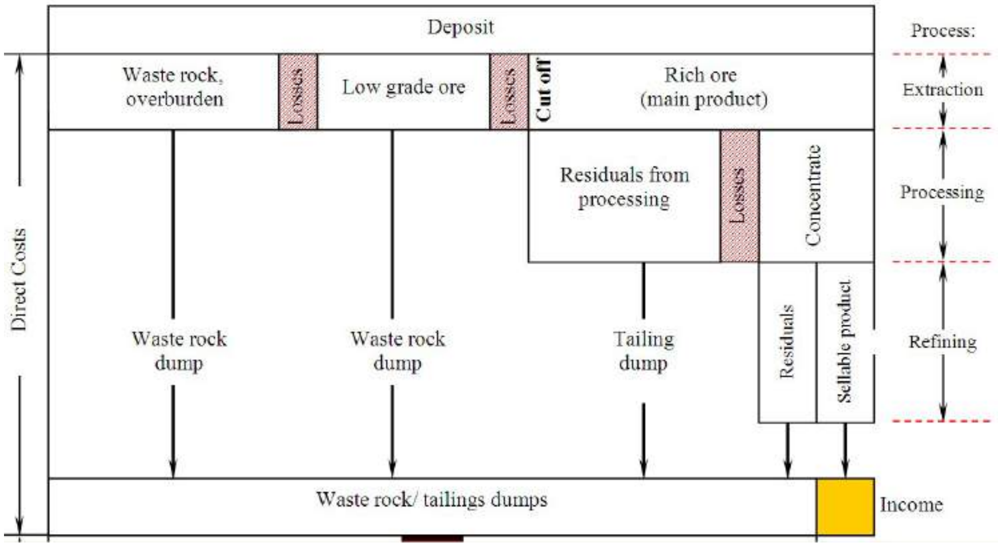


Fig. 1. General mining approach.

The main characteristics of this approach are:
− not optimized processes with relatively high losses of valuable components
− in result high volume of waste material
− with negative impacts to the environment
The indirect costs includes the expenditures, necessary for compensation of all negative influences of the mining project to the environment, like
− Land occupation costs
− Environmental protection costs/Health care
− Reclamation costs
− Long term costs (decrease of land value, climate change …)
− Monitoring costs
− Early end of deposit reserves/Early investment in new deposits
− **…**
Widely exists the opinion that for all negative mining influences, especially after mining, the government is responsible, because the companies pay/paid taxes to the government budget.
In Germany the principle is, that the causer is responsible for all negative impacts and therefore he must accumulate special funds after governmental control. The experience shows, that and after decades of mine closure not all problems are solved, e.g. with slope stability and water quality. The German government paid in last 25 years approx. 11 B€ for closing coal mines, more than 5.5 B€ for closing uranium mines, and another 2 B€ for closure of other metal (Cu, Sn …), spare, and salt imes. The mine closure was caused by the unification of Germany with the bankrupt of mining companies without financial funds for reclamation.
The economic parameters of the general mining approach are illustrated simplified in figure 2. The general tendencies are:
− than higher the extraction (recovery) rate of valuable components, than higher the income
− and then higher the direct costs because of additional measures
− the profits (economic zone) reaches a maximum in moderate extraction level
− considering the indirect cost, the profit reduces (ecological zone)

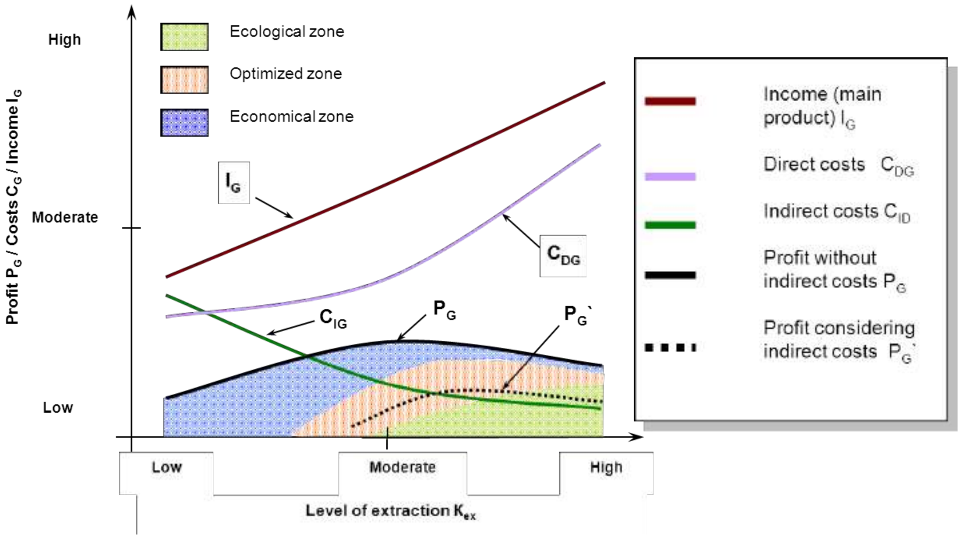


Fig. 2. Economic parameters of general mining approach, depending on extraction level.

3.2. Alternative mining approach

The main characteristics of the alternative mining approach are (formula 2, fig. 3):

– Increase of extraction level of main product/reduce losses
– Use of byproducts and accompanying products/reduce residuals
– Use of environmental clean production methods
– Fulfill all reclamation responsibilities like integrated part of mining
– Consideration and reduction of indirect costs
– Long term production/Past investments for new deposits

$$\text{(Moderate) Profit } P_A = \text{Income } I_A - \text{Direct Costs } C_{DA} - \text{Indirect Costs } C_{IA} \qquad (2)$$

The general tendencies of economic parameters of the alternative mining approach are simplified:

– higher income because of reduction of losses and additional sellable products from byproducts and accompanying raw materials
– reduce of indirect costs, because of less waste volume and contamination potential
– mainly less profit because of consideration of indirect costs and additional technical measures to achieve higher extraction level and higher environmental performance

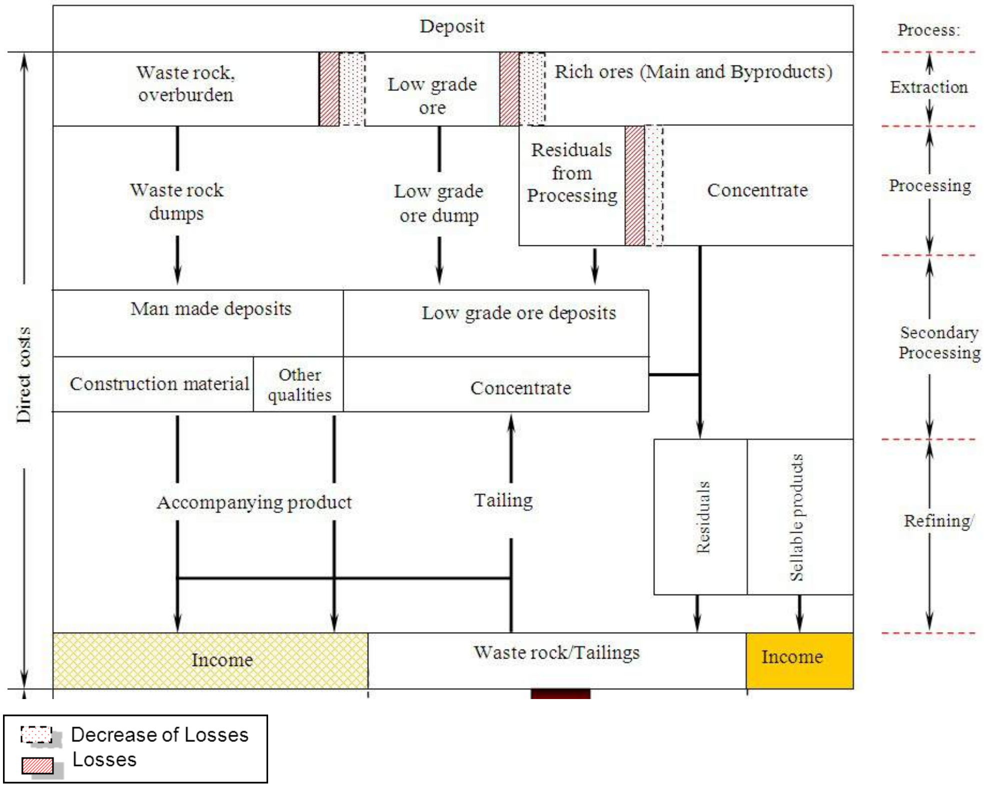


Fig. 3. Alternative mining approach.

Figure 4 shows a variation of direct and indirect costs, depending of the level of additional measures. In right balanced economies, higher expenditures for environmental friendly technologies result in significant decrease of direct costs, e.g. for energy and materials, and indirect costs.

The idea of “moderate profit” is that instead of “maximum profit” with low recovery rate and environmental and social responsibility, a part of the income is used to increase this parameters. This shall be the standard of every mining company, but in reality, we see often only a minimum of realization of the requirements.

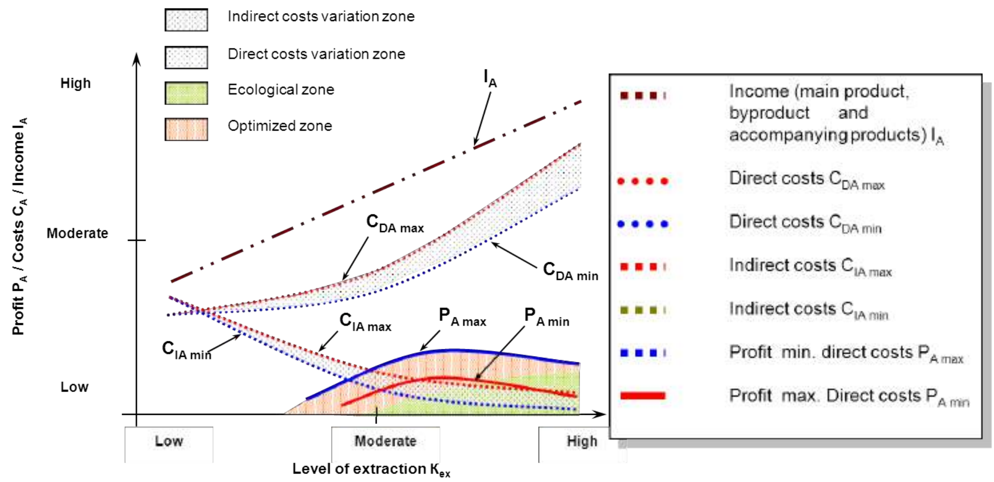


Fig. 4. Economic parameters of alternative mining approach depending on extraction level.

4. Sustainability Research in Mining

The chair surface mining at Technische Universität Bergakademie Freiberg understands sustainability in mining at first and foremost as responsible behavior of the mining companies, which takes into account the above-mentioned aspects of sustainability. Responsible for the promotion and support of this conscious action, the chair tracked in the following research strategy:

− Maximizing the use of value components of a deposit (major, minor, and accompanying minerals)
− Use of valuable minerals in the residues of raw materials extraction and processing
− Environmentally friendly mining technologies
− Ensuring public and occupational safety in all stages of the mining process
− Fast and high-quality rehabilitation of the claimed land

For this mining concept methodological basics were created, which have been published in books and international conferences. To implement the research priorities at the chair surface mining for the diverse topics are established interdisciplinary and internationally oriented research groups:

− Mine planning (operation research path)
− Mining technology (mechanical path)
− Mine water (chemical path)
− Raw material awareness/ education (social path)

4.1. Maximum utilization of the value components

The research focus "Maximum utilization of the value components" includes the following topics:

− Construction of a rock management system starting from the deposit model to the raw material processing to optimize the mineral recovery from deposits in compliance with the environmental benefits on the example of copper mining in Chile [1]

− Selective extraction of raw materials with high selectivity to avoid losses or dilution, e.g. hard coal mining in Vietnam, lignite mining in Germany [2;3]

− Optimization of extraction technology for safe use of reserves, such as extraction of pillars and low-loss extraction of high rooms (chambers) in the copper mine Sheskasgan, Kazakhstan

− Development of intelligent solutions for quality control in production and storage/ dumping processes [4]

− Targeted construction of technogenic deposits, such as for accompanying materials [5]

− Inclusion of low-grade ores in resource recovery, such as gold in Uzbekistan [6]

4.2. Use of valuable minerals in the residues of raw materials extraction and processing

In continuation of the target of maximum use of valuable deposit components of cause the residuals from processing, extraction or utilization of interest. Research topics are:

− Recovery of valuable components from tailings, e.g. Phosphorite in Uzbekistan [7]

− Use of residues from treatment, e.g. Phosphorite in Uzbekistan [8]

− Use of residues of raw material use, e.g. ashes [9]

4.3. Environmentally friendly mining technologies

Under the research focus "environmentally friendly mining technologies" are investigated the following topics:

− Environmentally friendly drainage technology (HDD filter wells to reduce the demand of material, energy and land) [10]

− Analysis of the cutting processes to reduce wear and dust as well as for energy optimization [11,12]

− Optimization of blasting technology to reduce emissions (vibrations, noise, gases, dust ...) with good fragmentation [13-15]
− Use of alternative fuels for mining equipment, such as biodiesel [16]
Investigations to reduce the noise on conveyor belts
− Development of filter equipment for fine disperse sediments to reduce energy consumption
− Selection of optimal technologies for the use of mining equipment and mining equipment selection for the optimal operating under given conditions [17]
− Environmental accounting for selection of environmentally friendly mining systems (example: hard rock and under water extraction) [18,19]
− Complex effects of small-scale mining on the mineral economy and justification of countermeasures [20]
− Development of holistic environmental management strategies [21]

4.4. Ensuring public and occupational safety in all stages of the mining process

Environmental and aspects of health and safety are close to each other. Selected research topics under the main aspect of health and safety are:
− Development of dump monitoring systems for early detection and risk mitigation of negative impacts; use of Neural Networks [22]
− Analysis of the cutting processes to reduce dust development
− Prevention of coal fires (on example of China) [23,24]
− Concept development to avoid accidences in surface mining on example of coal mining in Indonesia.

5. Fast and high-quality reclamation

The research focus on "Fast and high-quality reclamation" covers the following topics:
− Developing the basics for a “dump cadaster”/ “dump archive” for the evaluation of mechanical and chemical processes in dumps and appropriate countermeasures for adverse effects [25]
− Methods to reduce the formation of acid mine waters and effective methods for neutralization of acidic waters [26]
− Review of long-term consequences and tasks in the closure of mines [27]
− Optimization of mining technology to increase land reclamation area and reduce external dumps
Reclamation under the aspect of post mining regional development.

The stated objects of the research focus in part across themes. Further optimization of sub-processes is often only effective in the consideration of interactions with upstream and downstream processes. As an example, in particular the topics selective and cutting processes as well as rock management system or optimized blasting take this in to account. In the project rock management system for example work together experts in drilling, processing, mechanical process engineering and automation processes.
The topic of mining safety is the basis and prerequisite for any of the topics e.g. coal fires or residual pillar extraction.

4.6. Research methods

To solve these issues following methods are used:
− Laboratory, pilot and field tests
− Mathematical modeling and simulation
− Process visualization for understanding and optimization of processes
− Artificial intelligence (neural networks)
CAD, expert systems
− Financial-mathematical models, economic valuation
− Integration of suitable sensors for process monitoring and control
− Development of integrated mining planning and production management systems
With the selected research areas and topics the chair surface mining contribute to a responsible mining approach with balanced consideration of economic, environmental, social and safety aspects and to the responsibility, that even future generations can use the geo-materials.
In teaching this holistic approach is also taught. Serve e.g. the courses mine planning, mining abroad and mineral economics. In special courses will protected goods taken into account, for example mining water management, reclamation, and ventilation and security technology. Moreover, the aspects of sustainability are an integral part of the technical and technological courses.

5. Examples of Realisation of Responsible Mining Concepts

The institute of mining at Technische Universität Bergakademie Freiberg realized in last years several research and development projects in different topics along the process chain in mining (see chapter 3). Some of the projects short introduced below.

5.1. Comprehensive approach of Geometallurgy

The concept of Geometallurgy is, to close the information chain between the geological and mineralogical parameters of the deposit on one hand and the final extraction process of valuable minerals on the other hand. Mining is the bridge between the deposit and the processing plant. Then better the mining department know what are the requirements, then better the processes of loosening, loading, haulage and dumping/blending can be optimized. Often up to day exist a lack in information along the process chain and much information is not used in the process design. An independent information system was designed to keep the process information available and use the information for process optimization [1]. Figure 5 illustrates the principle of material and information flow.

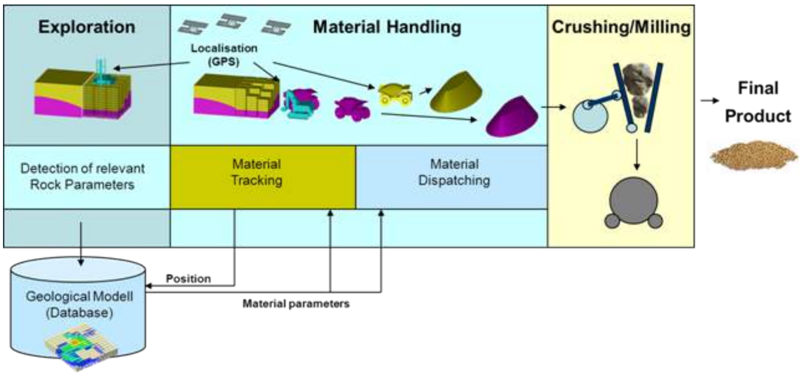


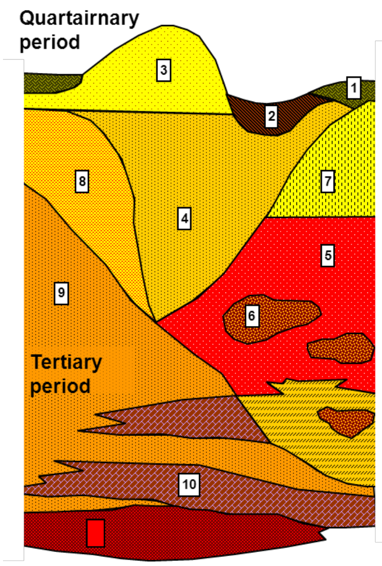
Fig. 5. Scheme of information and material flow in a typical mining project.

Especially in deposits with different mineralization zones, like in copper deposits, often not used selective processing of the ore, but the ore is blended in one stockpile. Investigations showed that the separate processing of ore types with different mineral grain sizes have economic and environmental advantages. The over mill of coarse ore particles with waste of energy and the not sufficient opening of fine ore particles with losses in the processing, can be reduced. Because milling is the most energy consuming process, the selective processing lead to economic and environmental benefits.

To the comprehensive use of the deposit belongs and questions of use of low grade ores. A selective dumping of low grade ores and waste rock is almost not realized everywhere. Low grade ores can in future periods of mine life, after decades, become economic interest, even, when prices for the ores and/or the costs for primary excavation grow up. A mathematical model for integration of low grade ore in the extraction process was developed [6].

5.2. Use of accompanying raw materials

The use accompanying raw material can give additional benefits to the mining project, e.g.
− additional income
− availability and cost reduction for own needs in the mine, e.g. for road construction
− reduce the volume/ costs for waste disposal
− reduce of land demand
− additional working places
− later development of new deposits
Figure 6 presents a typical case for accompanying raw materials in the overburden of German lignite mines [5]. In the permission documents, the use of the accompanying raw materials is an integrated part. The mining companies must undertake selective mining and dumping.



Accompanying product	Use of accompanying products
1. Top Soil	Reclamation
2. Peat	Fertilizer, Reclamation
3. Sand, aeolig	Construction material
4. Sand, alluvial	Construction material
5. Glacier Silt	Reclamation
6. Glacier Bolders	Decoration Stone
7. Sand, Gravel	Construction material
8. Gravel, alluvial	Construction material
9. Gravel, tertiary	Construction material
10. Clay	Ceramics, …

Fig. 6. Typical accompanying raw materials in overburden of coal mines in Germany and their use (table on right site).

5.3. Use of residuals of processing

On example of a phosphorus deposit were investigated the use of the residuals for soil improvement on one hand and of the secondary extraction on other hand. The content of phosphate after processing is still 10%. The processing residuals transported to the tailing pond.
Figure 7 shows the results of experiments for hydraulic sedimentation process control with the target to achieve a concentration of phosphate particles in the tailing and one of the possible technologies for extraction from the tailing site. The red part on left site shows the separate sedimentation and the buildup of a man made, secondary deposit of phosphates. The grade reaches up to 50%. Using the hydraulic diameter of particles, the sedimentation process can be mathematical described and controlled by the inclination of the beach, the relation of solid fraction in the suspension, the discharge volume and other parameters [7].
The alternative use of phosphate tailings is the direct use as fertilizer for the soil improvement. Figure 8 illustrate the influence of the application to the plant growth for different soil types. With an application of 20% of phosphate tailings was achieved an increase of plant growth up to 15% [8].
Other positive results were found using fly ash of coal burning for soil improvement [9].
The use of residuals can give similar positive results like accompanying raw materials.

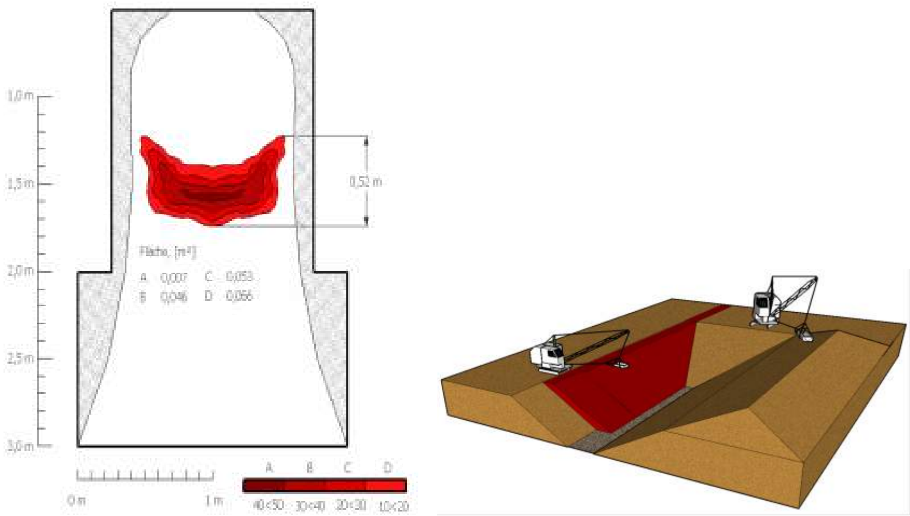


Fig. 7. Results of controlled sedimentation (left site) and proposed extraction method of the secondary deposit.

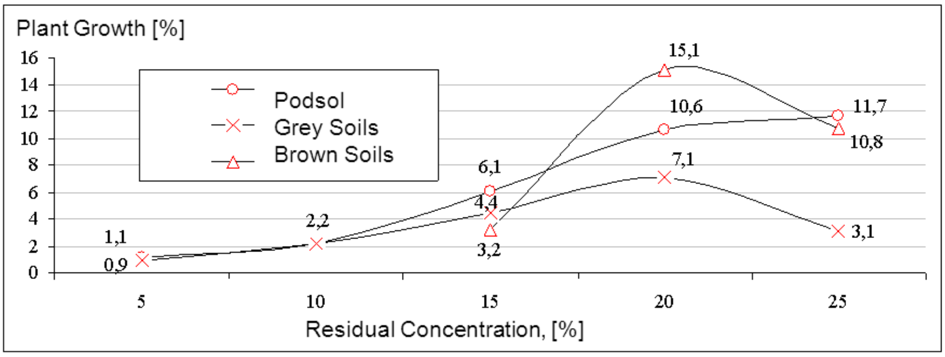


Fig. 8. Influence of mixing phosphate tailings in to different soil types on plant growth.

5.4. Improvement of mining technology

One of the main subjects for improvement of the mining technology is the investigation of the cutting process. The right cutting device can reduce the cutting resistance and in result the energy consumption, the wear and dust development. This improves the health, environmental and economic situation. The results of experiments show, that the cutting parameters und constructions of cutting devices influence to this parameters. The investigations were carried out for bucket wheel excavators and tools on ploughs and drums [28, 29]. Figure 9 shows the experimental stand for rock cutting with dust determination.

In practical application the change in cutting parameters and cutting devices lead to an increase of excavator output of up to 15% for each measure.

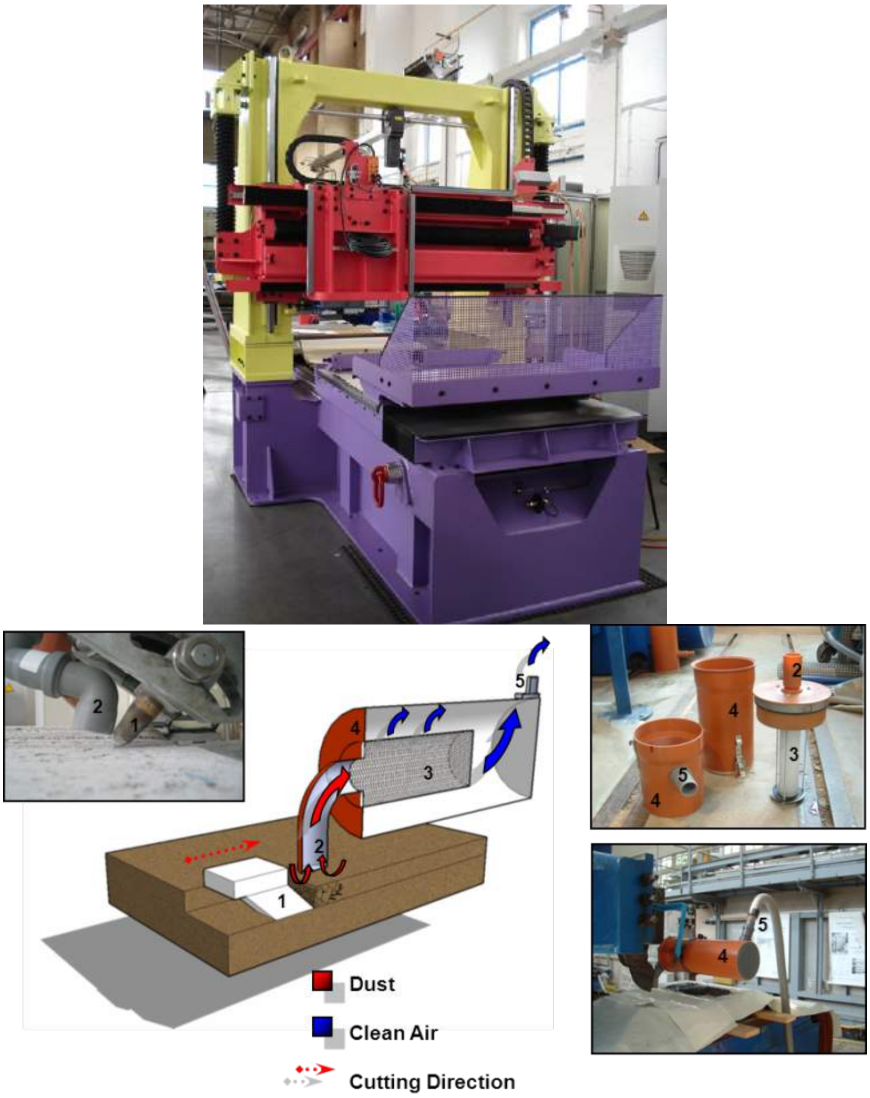


Fig. 9. Investigation of cutting resistance and dust emissions (left: test rig, right: dust collector)

Other investigations were carried out e.g. for the use of biodiesel in heavy mining equipment fleets.

5.5. Considering of post mining landscape design and AMD

In result of mining forms a post mining landscape, often with changes in mechanical, chemical, biological, morphological and other properties [27].

It is very important to reclaim the mining areas as soon as possible. A other very important question is the overburden management to create safe and valuable landscapes. Figure 10 illustrates a situation before and after refill of a uranium mine in Germany. From seven outside dumps approx. 120 M m^3 of rock were moved by heavy mobile fleet over 10 years back to the mine after mine closure.

Fig. 10. Post mining landscape (left: general approach; right: refill).

Another very good example of successful reclamation activities but during mine operation on inside dump is the relocation of the river Inde cross the dump.

More and more attention get the acid mine water drainage (AMD). The frame water regulation in the European Union requires strong parameters for water quality. A decrease in water quality is not allowed. In German coal mines for example the AMD results in very low pH-values and load of iron, sulfates and nitrates.

To avoid the negative influence on water bodies, the mining companies must undertake all practical proofed measures. The first step is to classify and dump the soil in suitable way. Secondary, during excavation, transportation and dumping of sulfide soils the exposition time and contact

intensity with oxygen and water must be reduced. Tertiary hot spots of AMD must be treated. The knowledge about the properties of excavated and dumped materials and their location is important, not only for AMD, but for geotechnical safety too [25]. This aspects must be considered in mine planning and surveying.
The development of integrated mine planning and control systems are not only important for landscape design but also for optimization of output the equipment [30, 31].

5.6. Evaluation models

For selection of the best available technology needs evaluation models. Figure 11 shows the general selection steps. The selection carried out after the definition of the system boundaries with an input-output analysis. The evaluation considers economic and environmental parameters. The weighting factors for different parameters defined depending on the real conditions. For example inert coarse dust particles or seismic effects have lower impacts in far distance to protected subjects. The noise of a blast is different of a noise of a hydraulic hammer [18]. The results of investigations shown in figure 12 for selection of environmental friendly technology for a hard rock mine with typical output in Germany of 300,000 t per year and with rock strength 20 MPa.

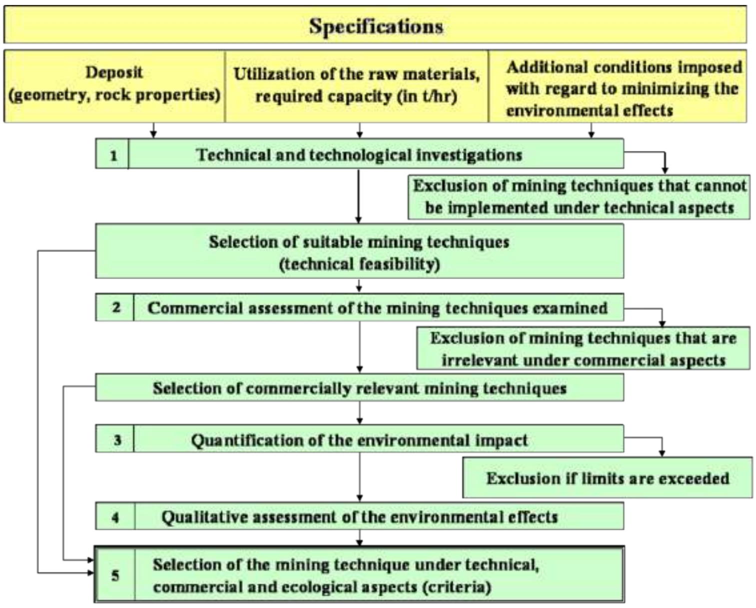


Fig. 11. Evaluation model for selection of environmental friendly mining technology.

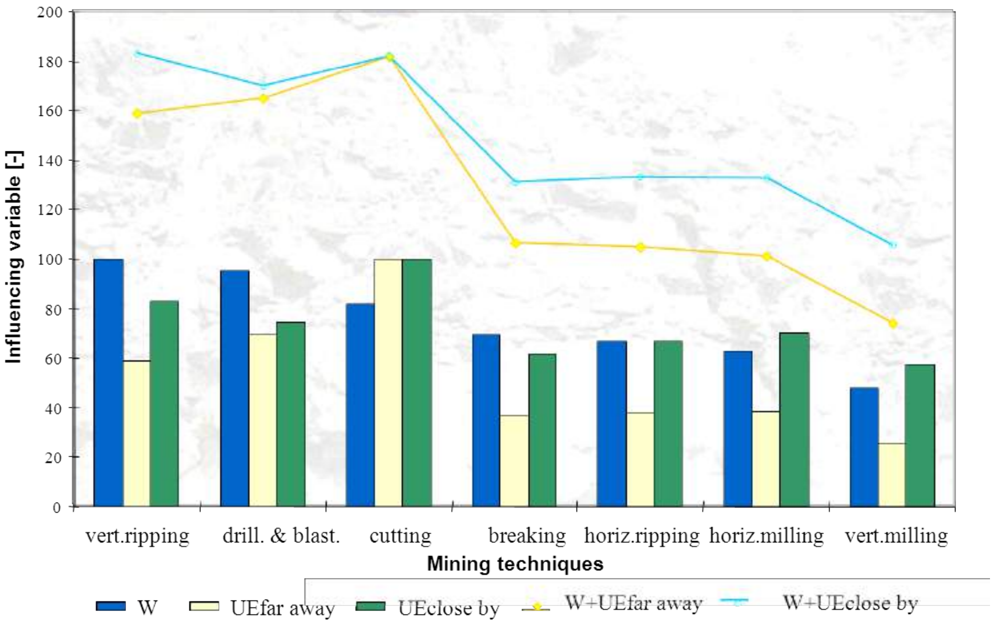


Fig. 12. Example of evaluation of environmental friendly mining technology.

Another evaluation model was developed to define the costs for long term mining impacts to create during mining operation a sufficient financial fund for fighting against negative influences, like AMD or slope instability [32]. Figure 13 shows the scheme for the mathematical calculation in accordance with formula 3.

$$AW = \sum_{t=1}^{T} \frac{A_{t\,(0)}}{q^t} \tag{3}$$

AW - expense parameter, €

$A_t(0)$ - periodic amount for the cash-layout costs and investments in period t at the valuation level in base year 0 (annuity), €

t - valuation period (year)

T - period

q - imputed interest (real rate of interest), %/a

A typical case study for using the model is the question: What is the best solution for everlasting dewatering measures, pumping or free water flow? In the first case the investment is lower and the operation costs are higher, in the second case the investment is higher but the operation costs are lower. In result the first case with a pumping station give the best results. Therefor the all investments and costs calculated year by year and transformed by formula 3 to an expense parameter. Very important are the determination of the interest rate and of the technical-financial risk of calculations. Often the interest rate is over estimated. The value is mainly in the range of 3%.

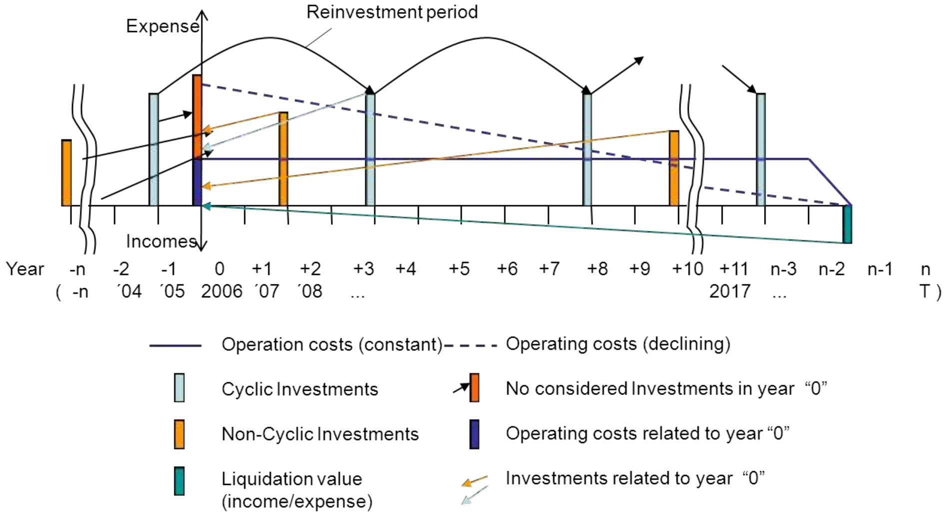


Fig. 13. Financial evaluation model for long term mining expenditures.

6. Conclusions

To optimize the mining process under considering of both, economic and environmental/social aspects, a comprehensive investigation of all processes along the process chain over the life cycle is necessary. Positive results can be:

− minimize losses and increase the extraction rate of valuable components in the deposit
− minimize negative impacts to the environment, health and safety
− improve the acceptance and responsibility of mining projects
− optimize the economic parameters

Two mining approaches are possible: with "maximum" or "moderate" profit. To achieve the results, the maximum profit is not always the best supervisor.

For the "moderate" profit approach several solutions for more environmental and social responsibility exist. Advanced technologies and research are available and need permanent improvement.

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