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METHODOLOGY FOR ASSESSING THE ENVIRONMENTAL EFFECTS DURING THE MINING OF SOLID ROCK BY TAKING INTO ACCOUNT NON-EXPLOSIVE MINING TECHNIQUES

Близкое расположение горно-добывающих компаний к территориям, используемым в коммерческих целях или предназначенных для проживания населения, природоохранным территориям, а также тот факт, что население становится все более и более восприимчивым к вопросам загрязнения окружающей среды, привело к негативному отношению к добыче полезных ископаемых. В первую очередь именно производство буровзрывных работ вызывает недовольство и ставит на повестку дня внедрение более экологически благоприятных методов разработки полезных ископаемых. Использование новых способов добычи без применения взрывных работ может рассматриваться в качестве альтернативы традиционным методам. Использование таких технологий является единственной альтернативой при работе на некоторых открытых разработках. Основным вопросом является выяснение истинных преимуществ данных технологий и взаимосвязи между возможным усовершенствованием природоохранных технологий с одной стороны и производственным потенциалом и себестоимостью с другой. Предполагается в целом оценить методы добычи твердых полезных ископаемых. Рассмотрены аспекты оценки добычных методов с точки зрения их себестоимости и воздействия на окружающую среду.

The close vicinity of mining companies to other sites that are used for commercial and residential purposes or to areas under conservation as well as the fact that the people become more and more sensitive to emissions have led to a negative attitude towards mining operations in the neighborhood. It is above all the use of drilling and blasting techniques that give rise to objections, in the course of which demands for more environmentally-friendly production methods have been voiced. It is in this context that production methods without the use of explosives are considered as an option. After all, the use of such production methods is the only alternative for some quarry operators. The question is what are the true benefits of these techniques and what is the relation between a possible improvement of the environmental effects on the one hand and the technological potential as well as the costs on the other.

It is intended to assess the mining techniques for solid rock in their entirety. This paper will therefore look at the aspects for assessing mining techniques in the context of their environmental impact and the costs.

Preliminary remark

The «**mining technique**» comprises the «extraction system» and the actual «mining operations» as its two components. An «extraction system» refers to the chain of equipment necessary to exploit a deposit. In general, this chain of equipment is made up of partial operations, such as hewing and digging out the rock (= loosening), loading, hauling (conveying) and pre-crushing. The component «mining operations» is characterized by the direction of the mining progress (i.e. vertical or horizontal), the sequence of starting the individual slices and the mode in which the extraction system progresses within a slice (parallel mining, surface bench mining, side-to-side mining).

The term **extraction technique** refers to the way how the rock is loosened, which can be done either by drilling, by blasting or by a technique without the use of explosives. Fig.1 illustrates the extraction techniques schematically.

When talking about «environmentally-friendly mining techniques» one has not necessarily and automatically any mechanical extraction techniques without the use of explosives in mind. But the application of environmentally-

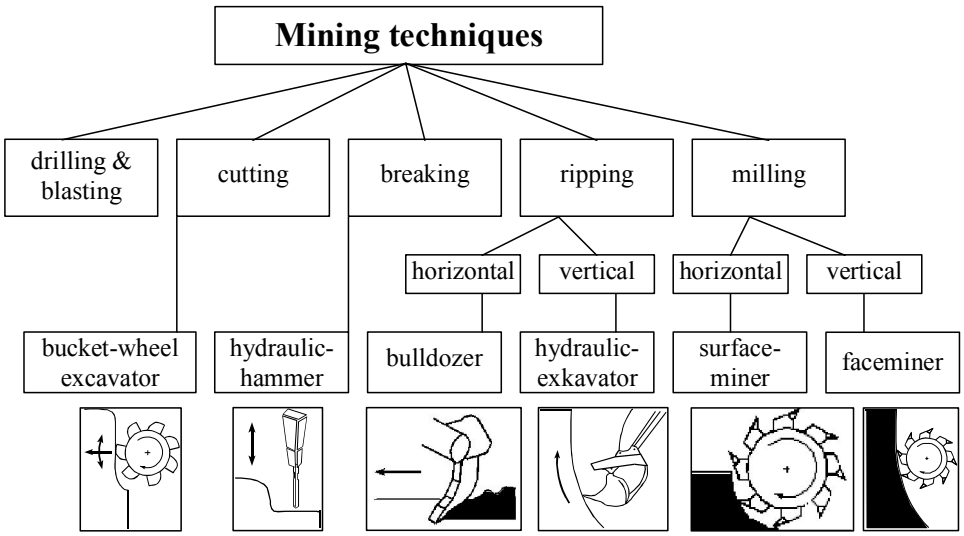


Fig.1. Extraction techniques for the mining of rock

friendly mining techniques is defined by the following aspects [8]:

A: avoiding or minimizing

– emissions into the atmosphere (exhaust gas, dust)

– noise

– vibration

– the contamination of the ground and surface water (and thus maintaining the water quality) and

– the creation of by-products (especially the share of non –marketable raw materials).

B: reducing

– the consumption of consumables (fuel, power, explosives, lubricants)

– the wear and tear

– the temporary use of land (earlier reclamation/renaturalization)

– the visual impairment of the landscape concerned and

– the production losses (careful use of resources).

In a narrower sense, this definition refers to all phases of the mining activities, beginning with the exploration, followed by the opening-up of the mine, the regular operations and eventually by the renaturalization/land reclamation, and looks also at the utilization or the consumption of operating equipment and consumables.

In a broader sense, the definition in includes additionally the phases of

– producing and disposing the operating equipment (loading, conveying and drilling equipment) as well as

– producing the consumables (energy, explosives, lubricants)

During these phases, both material and energy will be consumed and the environment will be affected by emissions into the atmosphere, by noise and by a destruction of the landscape.

Methodology for determining an environmentally-friendly mining technique

Fig.2 shows the flow chart for selecting an «environmentally-friendly mining technique». The annual production capacity (the output) of the open-cast mine to be assessed has been specified. Based on the deposit or the rock formation with its bonding or rock properties, the production capacity for each extraction technique will have to be established. The rock parameters, such as the compressive strength (one-axial compressive strength), the tensile and shearing strength, the modulus of elasticity and the bed rock parameters, such as the crevasse formation, the degree of withering and the formation of layers, all influence the loosening / breaking / cutting properties of the rock. In addition to that, the equipment weight and the loosening techniques are of the essence.

Further specifications, such as the utilization of the raw material and the resultant quality requirements as well as additional conditions

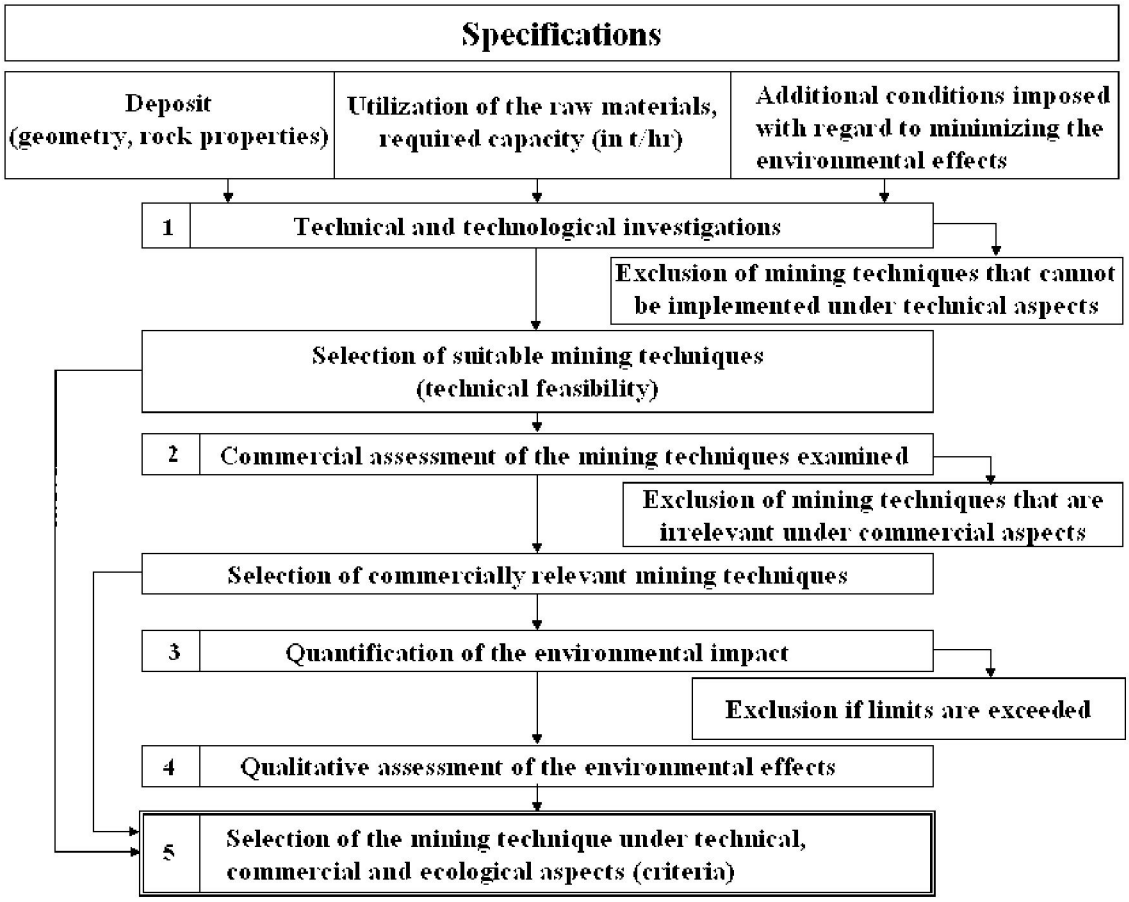


Fig.2. Flow diagram for selecting environmentally-friendly mining techniques

imposed with regard to the environmental impact, such as the compliance with certain limits, will have to be observed when selecting suitable mining techniques. The calculation of the production capacity for each extraction technique alone has proved to be difficult so far, since there is no model available that provides details about the capacity for loosening the rock, when a certain extraction technique is employed [2]. However, there are individual analyses, although most of them only look at one single extraction technique. This means that the compressive strength in connection with the existence of joint faces is of major importance [7]. Unfortunately, the capacity for loosening and loading the rock can only be determined to a certain extent by taking into account the rock or the rock formation with its relevant properties. The manufacturers of extraction equipment have their own methods to derive the loosening capacity of the machine concerned from the rock to be tackled. These methods are largely based on long-standing experience and cannot be applied ad lib to other machines. Certainty is eventually only gained on the basis of time and cost intensive onsite tests.

Numerous tests described in the literature as well as own practical experience make it possible to estimate the production capacity of a machine on the basis of the compressive strength and a description of the joint face structure, so that this methodology can be applied.

The technical/technological investigations will largely comprise the mining technique, which consists of the extraction system and the mining operations as its two components.

Mining techniques that cannot be implemented for technical reasons will be disregarded in all future considerations. Examples are soil class 7 and a low degree of joints and fissures, where a hydraulic excavator or a

bucket-wheel excavator can hardly be employed for direct mining, given the current state-of-the-art. The extraction capacity is far to low or the wear and tear would be forbiddingly high. An extraction output of more than 300 000 t/a is possible indeed with a 115 t hydraulic excavator in direct mining operations, where the rock has a high compressive strength and a high degree of joints and fissures [5].

The technically reasonable options will be examined under commercial aspects and on the basis of the methodology defined. This will include both static and dynamic cost analyses, with the static cost analysis examining the capital and operating costs. The dynamic cost analysis will be performed on the basis of the FMK method. Non-viable methods will be disregarded in all future examinations.

The commercial assessment will be followed, if possible, by a quantification of the environmental effects by way of an input-output analysis, during which the environmental effects will be considered (Fig.3).

The vibration (Vibration velocities) caused by drilling and blasting operations will be calculated with generally valid equations. The value of the Vibration velocity from drilling and blasting will still have to be compared with the standard values stipulated in DIN 4140, part 3. The vibration occurring with all other techniques can only be estimated under qualitative aspects [6].

The mean sound radiation level is an indicator of how to assess the noise emission, while the quantities of dust generated can be calculated with the help of the methodology contained in VDI standard 3790, sheet 3. In order to do so, the emission factors of the processes in the extraction system will be established [6].

The entire life process covering the generation of primary energy and raw materials right up to their utilization is recorded in the GEMIS database (Global Emissions Model of Integrated Systems), which also includes the auxiliary energy and the material input for the erection of plants as well as for the disposal processes. This database provides data for the diesel and power supply, the production of metal and plastic, which will be taken into account with regard to each and any extraction system considered [1].

Assessment

The assessment of an environmentally-friendly mining technique should not only take the environmental effects into account, but also economic/commercial and social aspects. As a

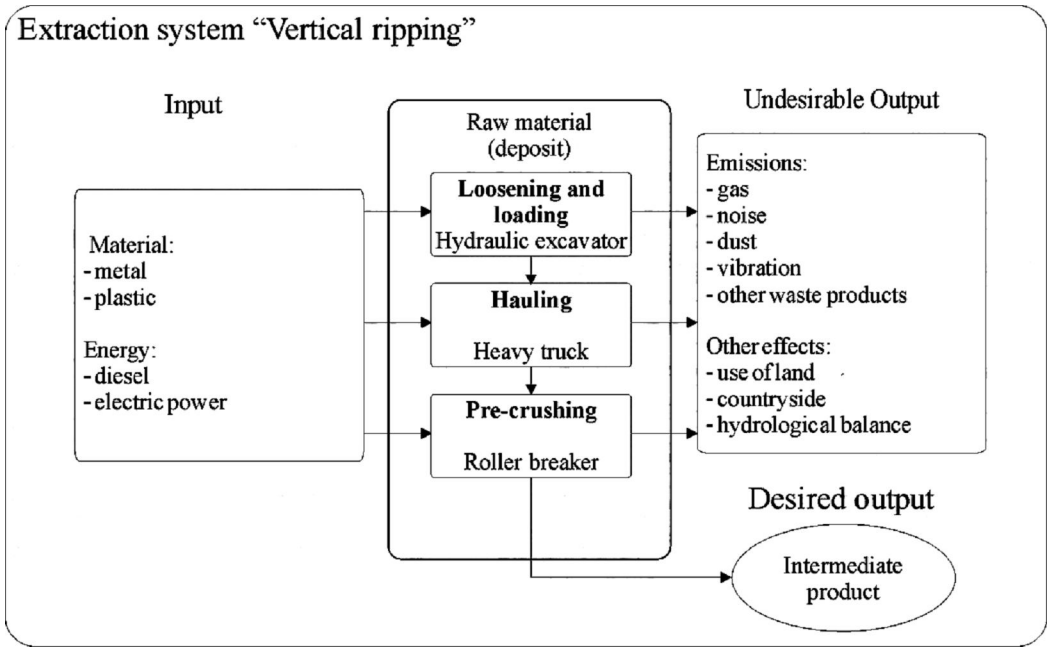


Fig.3. Input-Output analysis, using vertical ripping as an example

result of using machines and equipment and thus energy, emissions, such as CO_2, SO_2 and exhaust gas from the combustion engines, as well as noise, dust and vibration will be discharged or generated, respectively.

It is not possible at the moment to quantify all effects of extracting the rock or of the mining activities with acceptable effort. This is why the peripheral conditions for the assessment have to be determined and why only production costs and the environmental effects are to be directly taken into account as specific assessment criteria for the time being.

First of all, the criteria of each technological alternative are summarized in a table. In order to be able to use these criteria in an evaluation matrix, they have to be scaled. This can be done by using an ordinary or a proportional scale. On an ordinary scale, the values of the same type of criteria are compared with each other, with the values being assigned points by taking into account the ranking among those criteria. In that case, the relative differences between the values of the criteria will be lost, which is a disadvantage and leads to a distortion of the information gained. On a proportional scale, the values of the same type of criteria will be scaled in a differentiating way (environmental effects), so that the content of the information can be largely retained. Taking the noise level as an example, it will have to be noted that its increase by a mere 3 dB means twice the intensity. Table 1 shows an evaluation matrix. The technical alternative A_i with the lowest environmental impact U_j gets the highest number of point p_{ij}, i.e. 100 points as an example. Fewer points have been calculated for the other alternatives in accordance with the distance from A_i within the criterion. The points p_{ij} awarded for the environmental impact of each mining technique will then be added up vertically at the bottom of the table. This sum will represent the environmental impact of the relevant mining technique expressed in points, with the largest figure pointing to the least environmental impact, which must be assessed as positive in the sense of environmental friendliness.

In order to differentiate further, additional corrective and weighting factors need to be introduced, which are shown in Table 1.

The corrective factor k_{ij} takes the environmental effects of an environmental impact quantity U_j between the alternatives into account, thus taking care of the differences between the types of noise emissions or the types of vibration. The noise emission of a machine will have to be assessed differently than that of an explosion, to give just one example. Likewise, the vibration generated by a hydraulic hammer is different from that of a blast, both as far as time and intensity are concerned. The factor k_{ij} is thought to point out such differences, which will have to be verbally explained, if necessary.

Table 1: Evaluation matrix

	Alternative A_i		A_1	A_2	A_3	A_4	A_5
Range of a criterion	Criterion j	Weighting	k_{1j}	k_{2j}	k_{3j}	k_{4j}	k_{5j}
UE	U_1	g_1	p_{11}	p_{21}	p_{31}	p_{41}	p_{51}
	U_2	g_2	p_{12}	p_{22}	p_{32}	p_{42}	p_{52}
	U_3	g_3	p_{13}	p_{23}	p_{33}	p_{43}	p_{53}
$UE_{ges\ i} = \Sigma$			$\Sigma p_{1j}*g_j*k_{1j}$	$\Sigma p_{2j}*g_j*k_{2j}$	$\Sigma p_{3j}*g_j*k_{3j}$	$\Sigma p_{4j}*g_j*k_{4j}$	$\Sigma p_{5j}*g_j*k_{5j}$

UE: environmental impact

A: technological alternative (mining technique)

i: variant of the mining technique (e.g.:1 = drilling and blasting, 2 = horizontal milling,...)

U: environmental impact

j: type of environmental impact (e.g.: 1 = noise, 2 = SO_2 equivalent,...)

p_{ij}: points awarded to mining technique A_i and to the environmental impact U_j (takes the differences of U with regard to A_i into account)

k_{ij}: corrective factor for the type & intensity of the environmental impact, depending on A_i

g_j: weighting factor between the criteria U_j ; not depending on A_i

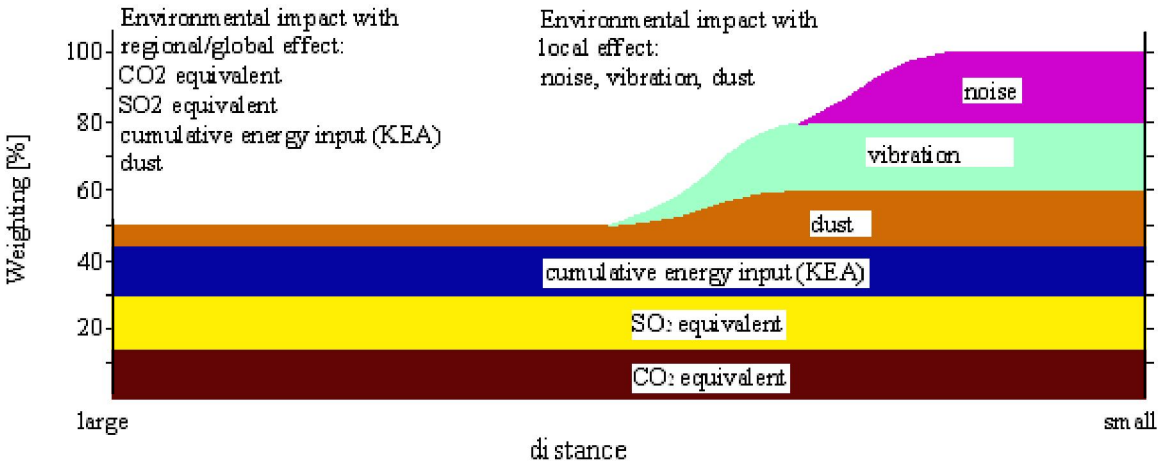


Fig.4. Weighting of environmental effects (diagram)

The weighting factor g_j weighs the criteria U_j against each other. One will have to consider what impact local or global environmental effects have on an object that is to be protected. The fixture of this factor depends eventually on the preferences of the decision-making person and/or the factor can also be established by questioning the persons concerned. The latter requires extensive surveying methods which shall not be detailed in this paper. Instead, two basically different cases will be looked at: The first one refers to a mining company that is located far away from any residential areas or an object to be protected. Here, local environmental effects, such as noise, dust and vibration lose their importance. In the second case, the open-cast mine is close to a residential area, so that local environmental effects need to be considered, apart from the regional and global ones. These differences will be taken care of by the weighting factor g_j (Fig.4).

The following general equation for the overall environmental impact caused by a mining technique can be defined from Table 1 and on the basis of the above passages:

$$UE_{ges\,i} = \sum_{j=1}^{n} p_{ij} g_j k_{ij} \,. \qquad \text{(Equ.1)}$$

The result of this analysis will be a matrix, in which the environmental effects of each mining technique are quantified by a non-dimensional number. It is now possible to find out by assessing the matrix, which of the techniques have the least environmental impact in toto, but also with regard to each individual criterion.

The economic/commercial criteria will be additionally taken into account by the addend $W_{ges\,i}$ in equation 2. This addend will eventually have to be established in accordance with the schema as shown in Table 1. It is also conceivable to observe the social advantages by way of introducing another addend $S_{ges\,i}$ into equation 2.

$$UEWS_{ges\,i} = UE_{ges\,i} + W_{ges\,i} + S_{ges\,i} \,. \qquad \text{(Equ.2)}$$

The procedure explained above will make it possible to establish the most environmentally-friendly, commercial and/or socially acceptable mining technique.

Application

One example has been selected to examine the environmental friendliness of extracting rock by looking at the processes of loosening, loading and hauling the material. The rock was loaded with a wheel loader with a bucket of 5 m³, while it was shipped on a heavy truck with a loading capacity of 24 m³. The mining techniques of vertical ripping, horizontal milling and cutting did not require any loading equipment, because the loosening and loading processes were jointly carried out by the loosening equipment. When examining the cutting process with the bucket-wheel excavator, the extraction system was examined with the equipment combination of a bucket-wheel excavator, a mobile conveyer and a belt conveyer system. Both the face miner and the extraction

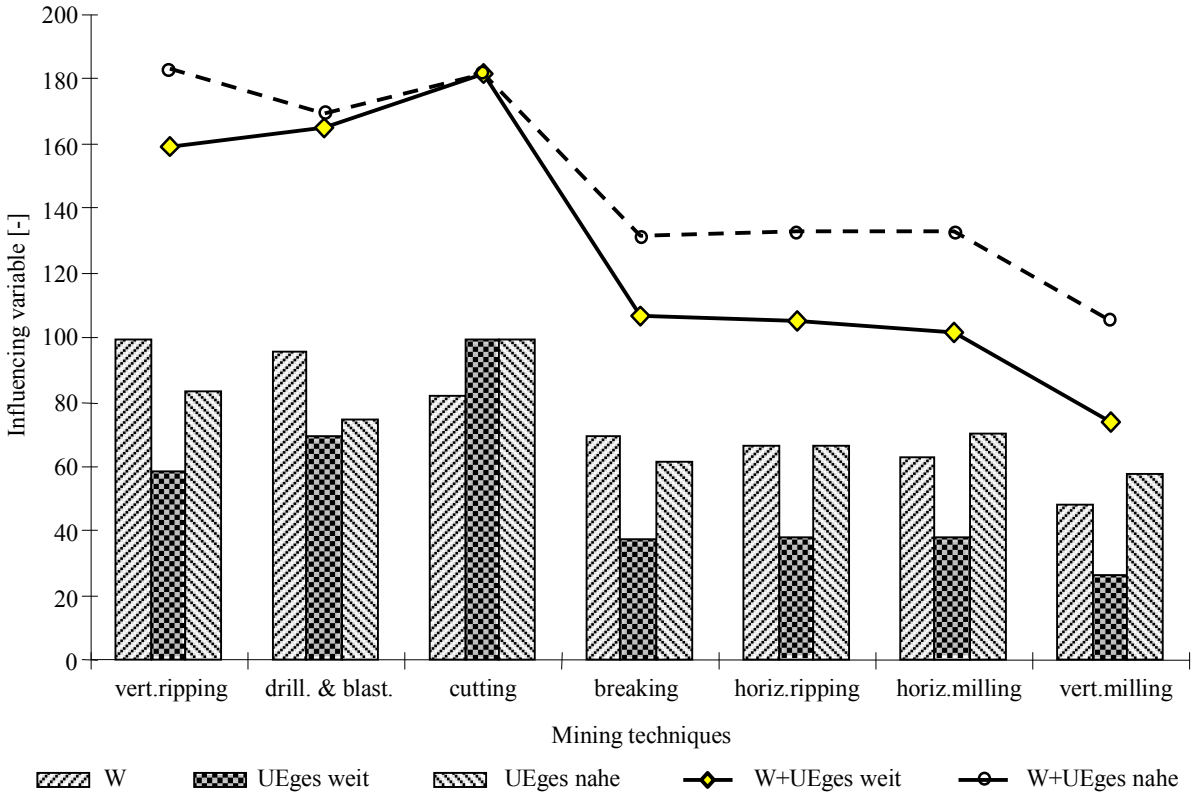


Fig.5: Presentation of the environmental effects and the costs after scaling the results

W:	economic impact value (production costs)
$UE_{ges\text{-}weit}$:	weighted environmental effects caused by the far-away open-cast mine
$UE_{ges\ nahe}$:	weighted environmental effects caused the open-cast mine close to sensitive objects (≈300 m)
W + UE:	Sum of the influencing values determined by the economy/commerce and the environment

system required power for the cutting operations, while all other extraction systems required diesel fuel.

It is assumed in the case of a fissured rock formation with a compressive strength of 20 MPa that each extraction technique as listed in Fig.1 will be applicable. The company's loosening capacity has been fixed at 300 000 t/a. The examinations have been carried out by taking environmental effects, such as dust, vibration, the CO_2 equivalent, the SO_2 equivalent and the cumulative energy input (KEA), into account. The costs (both operating and capital costs) have also been included in the assessment. The examination was based on inspections of open-cast mines for solid rock as well as on analyses made at the Mining University Freiberg (*TU Bergakademie Freiberg*) [3-5].

As has already been implied in section 3, the vibration was mainly established by qualitative rather than numerical values. It must therefore be assumed that the vibration (intensity) during the blasting is very high as compared with the other mining technique, although the highest degree of vibration among all mining techniques without the use of explosives is caused by breaking. However, the vibration caused by breaking is still much lower than that during drilling and blasting operations.

The environmental effects have been recorded on differentiating scales. The two cases assumed, i.e. the open-cast mine far away from human settlements and the one close to a residential area, make it necessary to weigh the environmental effects differently (Fig.4). Table 4 as well as Fig.5 show the effects of weighting the final results.

Table 2 shows the quantity units for examining and establishing the environmental effects and the production costs.

Table 2: Environmental effects and costs of the mining technique (quantity units)

	Drilling and blasting	Horizontal milling (surface miner)	Horizontal ripping (dozer)	Hydraulic hammer	Bucket-wheel excavator	Vertical milling (TSM)	Vertical ripping (hydraulic excavator)
SO_2 equivalent [g/t of rock]	8.0	15.1	13.5	15.4	1.4	8.9	9.2
CO_2 equivalent [g/t of rock]	948.3	1.598.0	1.449.7	1.647.4	505.2	2.177.5	993.2
KEA [MJ/t of rock]	10.6	20.8	18.9	21.5	12.7	32.4	13.0
Sound energy level [dB(A)]	112.9	114.0	113.5	114.6	108.5	114.0	110.7
Dust [g/t]	120.0	190.0	370.0	205.0	400.0	900.0	160.0
Vibration	within the limit	low	low	less than drilling & blasting	low	low	low
Production costs [%]	104.8	159.3	149.9	143.5	121.9	207.9	100.0

Table 3: Weighted environmental effects and costs caused by a close-by open-cast mine

	Weighting	Drilling and Blasting	Horizontal milling (surface miner)	Horizontal ripping (dozer)	Breaking (hydraulic hammer	Cutting (bucket-wheel excavator)	Vertical milling (TSM)	Vertical ripping (hydraulic excavator)
SO_2 equivalent	15 %	2.66	1.41	1.57	1.38	15.00	2.39	2.32
CO_2 equivalent	15 %	7.99	4.74	5.23	4.60	15.00	3.48	7.63
KEA	15 %	15.00	7.66	8.41	7.42	12.55	4.92	12.25
Dust	15 %	15.00	9.47	4.86	8.82	4.50	2.00	11.25
Sound energy level	20 %	19.23	19.05	19.13	18.94	20.00	19.04	19.61
Vibration	20 %	2.00	16.00	16.00	10.00	16.00	16.00	16.00
Sum (ranking)	100 %	61.88 (3)	58.33 (4)	55.2 (5)	51.16 (6)	83.05 (1)	47.83 (7)	69.06 (2)
Scaling	100	74.51	70.24	66.48	61.61	100.00	57.60	83.16
Costs (scaled)	100	95,45	62,77	66,71	69,67	82,01	48,11	100,00

As has already been mentioned, the costs must not be disregarded when an assessment is made on the basis of the environmental friendliness. Like the environmental effects, the costs have also been subjected to a differentiating scaling (Table 3), in which case the mining technique with the lowest production costs was awarded the highest number of points. A lower number of points was then calculated for the other mining techniques, depending on their difference to the most cost-effective technique, which is shown in Fig.5. The scaled presentation of the calculations shows vertical ripping as the most cost-effective mining techniques. The distance (or difference) to drilling and blasting amounts to approx. 5 points (i.e. 6 Cent/t) and low in comparison with the other techniques. Cutting with the bucket-wheel excavator takes the third place.

Cutting with a bucket-wheel excavator is the most environmentally-friendly mining technique, when looking at the weighted results of the environmental effects caused in both the far-away open-cast mine and the open-cast mine close to a sensitive object. This can be attributed to the use of electric power in the extraction system. The second place is taken by drilling and blasting in the far-away open-cast mine, and the third place by vertical ripping. If the open-cast mine is closer to a human settlement or to any other sensitive objects, the order of the environmental friendliness changes. While the first place remains unchanged, the second place is taken by horizontal ripping and the third one by drilling and blasting. This is largely due to the vibration caused by the blasting that is clearly higher than that caused by any other mining technique. The high degree of vibration caused by blasting can become a problem the closer the distance between the open-cast mine and the sensitive object concerned is, which, in turn, may jeopardize the continued validity of the extraction license. Although the report of the explosion (the bang) has been disregarded for this assessment, the noise emission values for blasting activities in a residential area, in a mixed area or in a recreational area would have to be observed in any case. As an explosion is a short-term event, the standard emission values may be exceeded in accordance with VDI 2058, sheet 1, by a maximum of 30 dB during the day. A minimum distance of approx. 150 m is required for blasting operations in villages and mixed areas. In accordance with the assessment methodology (as detailed in Fig.2), any technique by which a limit is exceeded would then be disregarded.

The comparison of the environmental impact of the individual mining techniques shows that the relative differences of a far-away open-cast mine are much higher than those of an open-cast mine near a built-up area.

Fig.5 makes it clear that cutting, vertical ripping as well as drilling and blasting take a top position among the mining techniques in both cases under examination (a far-away and a close-by open-cast mine) as far as costs and environmental effects are concerned, with drilling and blasting in the vicinity of a town or a village being less favorable than in a far-away place. The most cost-effective mining technique employed in an open-cast mine close to a sensitive object is the second-best as regards its environmental friendliness.

Fig.5 also illustrates a trend indicating a connection between the influential factors determined by the economy and by environmental friendliness. The mining techniques with the lowest environmental impact are also the most cost-effective ones and hence socially most acceptable. This relationship has only been proved in this example and is to be verified by further investigations.

Summary

The close vicinity of mining companies to areas given over to other uses, such as residential areas or nature reserves, have triggered a negative attitude of the population towards rock mining companies. Demands for the use of environmentally-friendly mining techniques are increasingly voiced and reference is made to extraction techniques without the use of explosives in this connection.

Based on the definition of what an environmentally-friendly mining technique is supposed to be, this paper presents a methodology that contains technical/technological, economic/commercial and ecological investigations into different mining techniques. When assessing a mining technique in accordance

with its environmental friendliness, the analysis should also take social factors into account, apart from economic/commercial and environmental ones. If necessary, these aspects should be differently weighted within the overall assessment and looked at in their entirety. This relationship requires further investigations into and analyses of the rock mining sector.

With the help of the described methodology, six mining techniques in addition to drilling and blasting have been examined with regard to their production costs and the environmental effects caused by SO_2, CO_2, the cumulative energy input (KEA), noise, vibration and dust, in which case a model of a deposit in a fissured rock formation with a compressive strength of 20 MPa was used. The intention was to gain quantitative data wherever possible. These data were scaled and fed into an evaluation matrix, in which the environmental effects were weighted differently. The results were then assessed in the light of two fundamentally different cases, one being an open-cast mine close to sensible objects, say a town or a village, and the second one being a remote open-cast mine. The local and regional/global environmental effects have been weighted in both cases. As a result of the analyses, the most cost-effective and most environmentally-friendly mining techniques close to and far away from a residential area as well as the most environmentally-friendly mining technique have been established for the two assessment cases by also taking the production costs into account. Vertical ripping, drilling and blasting as well as cutting proved to be the most cost-effective mining techniques and also the most environmentally-friendly ones in operations with a production capacity of 300 000 t/a.

Looking ahead

Taking a model deposit as an example, this paper introduces a methodology for technical/tech-nological, economic/commercial and ecological investigations. It also discusses the relationship between mining techniques on the one hand and economic/commercial, environmental and social aspects on the other.

It is planned in the future to examine the use of mining techniques in other deposits by taking different properties of the rock formations and production capacities into account. It is intended to verify the relationship between the influence environmental factors have and commercial aspects when rock is extracted in mining operations. The differentiating assessment of the environmental effects and the commercial aspects are intended to be further adapted to each other. In order to carry out an assessment in its entirety, social aspects are to be looked at as well.

Depending on the rock properties in compact rock formations with a high compressive strength, drilling and blasting seems to be the only reasonable mining technique. In this respect, this methodology offers further ways of examining the extraction system as such more closely in the future.

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