METHODS FOR DETERMINING AN OPTIMAL TECHNOLOGICAL SOLUTION FOR UNDERWATER MINING

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ABSTRACT. The key factors which determine the choice of an optimal technical scheme for underwater mining have been analysed. Several methods for multi-criteria analysis have been used in this research, depending on the specific mining conditions. The different methods for establishing an optimal decision have been compared and their pros and cons have been analysed.

Keywords: underwater mining, multi-criteria decision analysis

МЕТОДИ ЗА ОПРЕДЕЛЯНЕ НА ОПТИМАЛНО ТЕХНОЛОГИЧНО РЕШЕНИЕ ПРИ ПОДВОДНИЯ ДОБИВ НА ПОЛЕЗНИ ИЗКОПАЕМИ

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РЕЗЮМЕ. Анализирани са основните фактори, определящи избора на оптимална технологична схема при подводния добив. Използвани са методи на многокритериален анализ, като са взети под внимание специфичните условия на находището. Различните методи за избор на оптимално решение са сравнени по между си и са посочени техните положителни и отрицателни страни.

Ключови думи: подводен добив, многокритериален анализ

Introduction

The choice of a suitable type of equipment and its corresponding extraction technology in the underwater mining of mineral resources has a significant importance about the overall result from the mining activities. On the one hand, this is related to the high responsibility, which comes with the amount of capital required for investment in the mining equipment. On the other hand, the effects on the environment from the mining activities are irreversible and this could lead to a negative outcome with a large scale effect. The increased requirements for the artificial footprint on the environment especially due to the mining activities are a serious limiting factor for underwater mining. Nevertheless, the development of modern-day technologies and mining equipment provides the possibility for extracting minerals in harsh conditions as well as the maintenance of the artificial footprint in certain predetermined boundaries. It is considered that some types of modern mining equipment not only reduce the ecological threat, but also provide good working performance and good revenue. In order to choose the most adequate mining technology and equipment for a certain deposit, the main factors should be considered individually for every type of mining equipment. Although, the individual approach is related to the consideration of many possibilities due to the great number of factors for every deposit, certain general conclusions and relations could be drawn from researching the decision making process.

Stages of the decision-making process

Based on an analysis of different sources, related to the underwater mining technologies, several stages of determining the most suitable mining equipment could be pointed out (Koprev, 2017).

The first stage includes the consideration of the technological factors of the deposit, determining the possibility of its extraction. These factors are determined by the possible technological schemes for extraction as well as the different types of mining equipment suitable for the conditions. Table 1 represents the most commonly used types of mining equipment and their application for exploiting different types of deposits. The deposits are separated into three main groups (river deposits, lake and sea deposits, deep sea and oceanic deposits). This classification is based on the distance of the deposit from the land and its depth (Koprev, 2017; 2018).

Table 1. *Mining equipment utilised in different conditions*

Types of utilized mining equipment	River deposits	Lake and sea deposits	Deep sea and oceanic deposits
1.Bed leveller	+	+	-
2.Pontoon dredger	+	+	-
3.Grab pontoon dredger	+	+	~ (experimental stage)
4.Multiple-bucket dredger	+	+	-
5.Suction dredger	+	+	-
6.Specialised vessels with mechanised or hydraulic cutting and suction pipes	-	+	+ (dissatisfactory results)
7.Specialised deep-sea robots	-	-	+ (experimental stage)

(+) – successfully utilised; (-) – unsuccessful utilisation; (~) – utilised in specific conditions

It is necessary to add that the results in the table determine the current level of technical and technological development and it is not definitive as some of the types of equipment are still in experimental period.

The second stage of the decision making process should consider the factors, related to the ecological effect of the mining technology. This stage has a significant importance as it eliminates some of the possibilities considered in the first stage. It is considered that the ecological impact resulting from underwater mining has a large-scale effect, but it has not been fully researched yet. To this moment researches have shown that the utilised technologies for mining from the seabed lead to irreversible changes which could potentially result in the death of the sea microflora and microfauna. Hence, at this stage, these types of mining equipment are not yet applicable for underwater mining in deep-sea conditions. On the other hand, some shallow underwater deposits are exploited because certain extraction technologies have proven that they can prevent the negative effect from an ecological point of view. They reduce the negative impacts ofre-sedimentation and the water muddiness by the use of special curtains which isolate the area impacted by the extraction process. Capsulated excavator buckets also prove to minimise the ecological impact (Bray, 2008). These technological solutions are applied in conditions where the ecological requirements are met. Those modifications of the standard types of mining equipment are the remaining alternatives in the decision-making process.

After determining the acceptable mining technology for exploiting a certain deposit from an ecological and technical point of view, one should consider the factors from **the third stage** of the decision-making process. This stage of the process involves the economic parameters related to the choice of the mining technology – revenue, costs, ore loss, etc. Thus, out of the remaining variants, the alternative, which is considered to be the most suitable one from an economic point of view, is chosen. This is related to the working performance of the types of mining equipment and several parameters which include the highest cutting precision, leading to minimal ore loss and a higher revenue. Other parameters could be considered as well, which further minimise the negative impact on the environment.

Parameters determining the decision

In order to establish a grounded decision for the choice of suitable mining equipment for a certain deposit, several key parameters should be considered. In this article 4 main groups of parameters could be established for the decision making process. The four groups represent certain characteristics of the mining equipment and should be considered in a complex manner regarding the full analysis of the most suitable mining technology. The groups are divided into:

1) Characteristics of the equipment – mining depth, rock output, cutting force, cutting precision, etc. (H_1);
2) Environmental impact – sedimentation, noise, gas emissions, etc. (H_2);
3) Economic efficiency – total costs, revenue, ore loss, dilution, etc. (H_3);
4) Social factors – safety factors, personnel qualification, etc. (H_4).

Methods for decision-making

These groups of parameters provide the establishment of a complex assessment of the types of mining equipment for a certain deposit. A quick way for establishing a complex numeric value for the different characteristics is by applying the proposed method in Table 2.

Table 2. *Assessment points for the mining equipment*

Assessed mining equipment, A_i		A_1	A_2	A_3	A_4
Characte-ristics	Weight				
H_1	w_1	P_{11}	P_{12}	P_{13}	P_{14}
H_2	w_2	P_{21}	P_{22}	P_{23}	P_{24}
H_3	w_3	P_{31}	P_{32}	P_{33}	P_{34}
H_j	w_j	$S_1=\sum P_{j1}.w_{j1}$	$S_2=\sum P_{j2}.w_{j2}$	$S_3=\sum P_{j3}.w_{j3}$	$S_4=\sum P_{j4}.w_{j4}$

H_j – assessed characteristics for the mining equipment;
j – number of assessed characteristics;
A_i – the reviewed alternatives of mining equipment considered for the deposit;
i – number of alternatives for mining equipment;
w_j – weight for the characteristics;
P_{ji} – points for characteristic j of mining equipment i.

The points P_{ij} are formed by applying the following relation: $P_{ij} = \frac{H_i}{H_{i\,max}}.100$, where $H_{i\ max}$ is the highest value of each characteristic for the group of alternatives. An important condition is that the sum of all the weights should be 100%: $\sum w_j$ = 100%, as well as that all the characteristics should be unidirectional (the improvement of the characteristic should be related to higher values of its corresponding points). Depending on the end result the sums of all the points for each alternative are arranged in a descending order (Trapov, 2011). The best possible alternative is the one with the higher sum S_i.

A method which is often used is the one, where a complex value could be established by representing the different alternatives as points in the n-dimensional space A(H_1, H_2, H_3, H_4). It is assumed that an ideal point exists, which represents the ideal alternative for the deposit I($H_{1\ ideal}$, $H_{2\ ideal}$, $H_{3\ ideal}$, $H_{4\ ideal}$). The alternatives are arranged depending on their distance from the ideal point. The shortest distance represents the alternative which is closest to the ideal solution. The distances (R_i) for each alternative could be calculated in the following way:

$$R_i = \sqrt{\left(1 - w_1 \frac{H_{1i}}{H_{1\,ideal}}\right)^2 + \left(1 - w_2 \frac{H_{2i}}{H_{2\,ideal}}\right)^2 + \left(1 - w_3 \frac{H_{3i}}{H_{3\,ideal}}\right)^2} \quad (1)$$

The points which each alternative gets, depending on its distance to the ideal solution, are calculated by using the formula:

$$P_i = \frac{1}{1 - R_i}.100 \quad (2)$$

An important requirement for using the method is that the considered characteristics of the mining equipment should be independent. A major flaw of the implementation of the method is the considered way for determining the values of the weights for the different characteristics. An easy way is to establish the values by applying the subjective approach. However, this method usually proves to be very inaccurate. In order to establish the correct values for the weights, a factor analysis based on statistical data should be implemented or a sensitivity analysis considering the end-result of the mining process (rock output or revenue) should be applied.

It is advisory that this method is used for arranging the alternatives only when the decision-making process is provided with full information about the specific conditions of the deposit. However, this approach is limited as it does not account for the possible changes that could occur while the exploitation of the deposit takes place. That is why, a stochastic approach is more suitable for considering the best possible alternative in accordance with the limited information which the decision-maker has.

Each characteristic H_j for every alternative has values which fall into the interval [H_{jmin}, H_{jmax}]. Hence, the grade which each alternative gets should be in the interval [$P_{j\ min}$, $P_{j\ max}$]. This leads to the formation of different cases where the mining equipment alternatives are arranged and each case is valid and possible under certain circumstances. This requires that a different approach should be used in order to get a grounded decision, although the information is incomplete. Hence, it is suitable to apply the game theory approach.

In the game model it is assumed that the first player is the decision-making person (the engineer), whose strategies are the choices of the different types of mining equipment (A_i). The other player is the "nature", which is represented by its strategies for the different possible scenarios for the conditions of the deposit (U_k). Each scenario U_k is related to a certain combination of characteristics (H_1, H_2, H_3, H_4) for each type of equipment i, and their corresponding points P_1, P_2, P_3, P_4, which are determined by its work performance under these conditions. Each scenario for the deposit's conditions is related to an individual grade S_i for the types of equipment. Table 3 represents an exemplary game matrix:

Table 3. *Game matrix for the alternative strategies for choosing the type of equipment according to the conditions*

		"Nature's" strategies (deposit's conditions)		
		U_1	U_2	U_3
Alternatives for the types of equipment	A_1	S_{11}	S_{12}	S_{13}
	A_2	S_{21}	S_{22}	S_{23}
	A_3	S_{31}	S_{32}	S_{33}
	A_4	S_{41}	S_{42}	S_{43}

For finding out the most suitable decision several criteria could be used: **optimistic criterion**: $\max_i \max_j (S_{ij})$; **Wald's maximin model**: $\max_i \min_j (S_{ij})$ and **Hurwitz's criterion**: $\max_i(\lambda \,.\, \min_j (S_{ij}) + (1- \lambda).\, \max_j (S_{ij}))$.

The optimistic criterion is used when the information of the deposit's conditions is full and the established decision is based on the best possible solution. It is not advisory that this criterion is used in the situation when there is not enough information about the deposit. Wald's model is also known as the "rational pessimist" during the decision-making process and it is suitable when the information is limited and no further information can be collected. Hurwitz's criterion is recommended in the scenario where the risk could be assessed with a certain numeric value. A number is considered for the coefficient of pessimism $\lambda \in [0;1]$. The optimal solutions for each criterion are the ones which apply to the condition of a saddle point in the matrix as the decision-making process takes place only once and the strategies should be clear. If the solution corresponds to a mixed strategy, a thorough comparison analysis of the different alternatives should be made in order to choose the most suitable one.

Conclusion

In conclusion, the decision-making process in the conditions of underwater mining is similar to the one in open-pit and underwater mining (Koprev, 2018; Stefanov, 2016).

However, a great importance is put on the ecological aspect of the mining process. That is why, the different stages of considering the possible alternatives for exploiting a certain deposit should be considered in the following order: considering the technologically possible mining technologies, eliminating those alternatives which are related to an unacceptable level of environmental impact, and choosing those alternatives which provide satisfactory working performance and revenue.

The proposed methods could be used as a solution for a real decision-making problem, but certain drawbacks need to be considered when applying the methods. For example, the subjective character of the weights of the different characteristics, as well as the incorrect determination of the work performance, depending on the conditions of the deposit, are key factors which could lead to wrong conclusions, if their values are not properly determined. Furthermore, it is expected that when different criteria are used in the game matrix some of the optimal solutions may differ from one another. This leads to the following cases: 1) If the different criteria point out the same optimal solution, this solution is considered to be the optimal one; 2) If the different criteria point out different solutions, it is advisory that the criteria should be reconsidered whether they are adequately related to the conditions of the deposit.

Furthermore, the points for each alternative should be recalculated in order to get adequate solutions. It is important to notice that this method is suitable for independent values and if it is applied for dependent values, there is a possibility that the result may not be the desired one. Hence, the results should be considered with a bit of scepticism.

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